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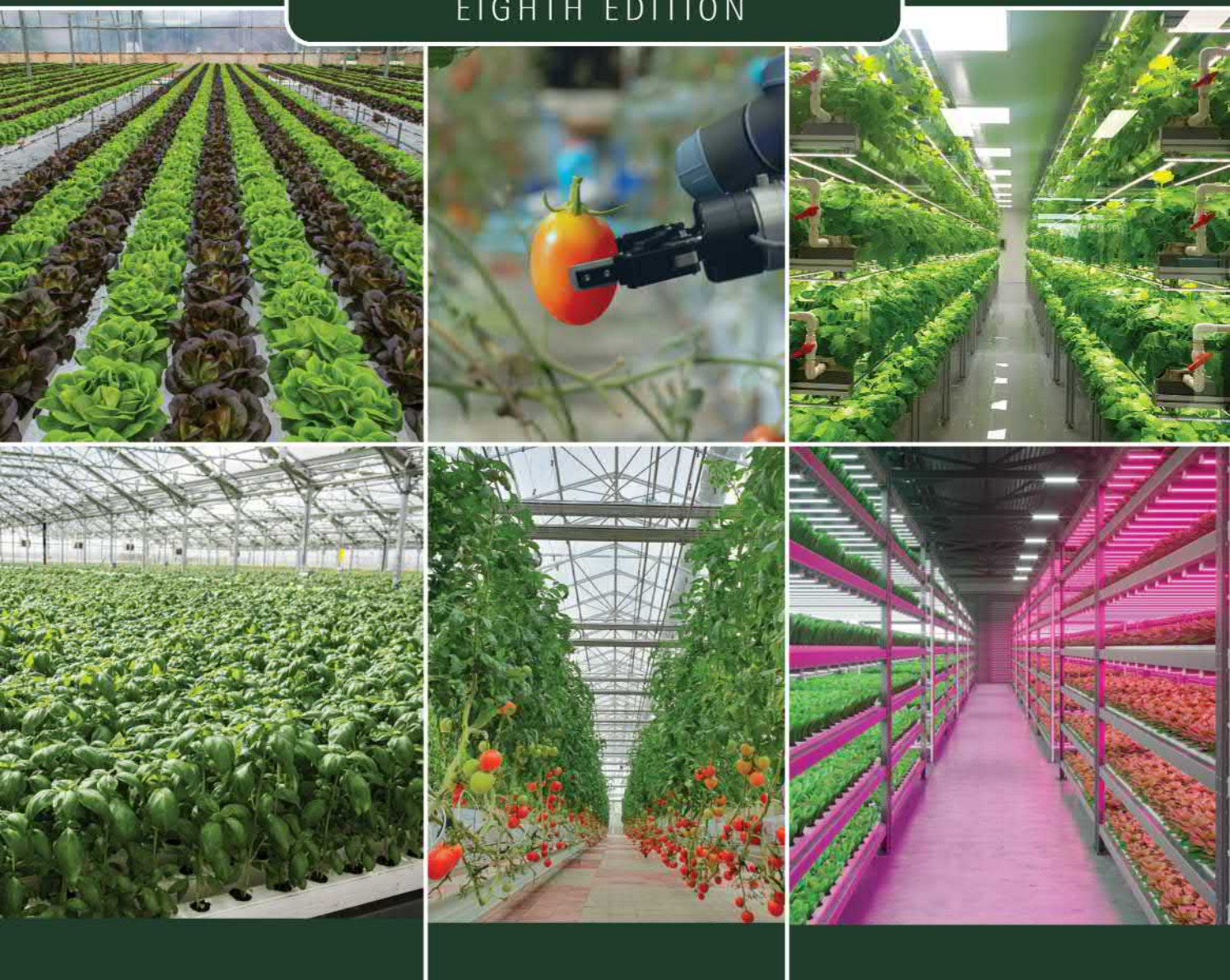
Howard M. Resh

Hydroponic Food Production

A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower

EIGHTH EDITION



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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

Eighth edition published 2022
by CRC Press
6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL 33487-2742

and by CRC Press
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

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Seventh edition published by Routledge 2013

CRC Press is an imprint of Taylor & Francis Group, LLC

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Library of Congress Cataloging-in-Publication Data
Names: Resh, Howard M., author.
Title: Hydroponic food production: a definitive guidebook for the advanced home gardener
and the commercial hydroponic grower / Howard M. Resh.
Description: 8th edition. | Boca Raton, FL : CRC Press, 2022. |
Includes bibliographical references and index.
Identifiers: LCCN 2021034735 (print) | LCCN 2021034736 (ebook) |
ISBN 9780367678227 (hardback) | ISBN 9780367678753 (paperback) |
ISBN 9781003133254 (ebook)
Subjects: LCSH: Hydroponics. | Food crops. | Handbooks and manuals.
Classification: LCC SB126.5 .R47 2022 (print) |
LCC SB126.5 (ebook) | DDC631.5/85–dc23
LC record available at https://lccn.loc.gov/2021034735
LC ebook record available at https://lccn.loc.gov/2021034736

ISBN: 978-0-367-67822-7 (hbk)
ISBN: 978-0-367-67875-3 (pbk)
ISBN: 978-1-00-313325-4 (ebk)

DOI: 10.1201/9781003133254

Typeset in Times
by Newgen Publishing UK

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Preface

The first edition of this book was published in 1978. Its last edition, the seventh, was revised in 2012. The eighth edition has undergone significant updates to keep it state of the art in the field of hydroponics. The author has maintained the book in its same format, but expanded many of the chapters and added two new chapters (Chapters 12 and 14) on greenhouse environmental control and vertical indoor farms. Also, updates on the sustainable yield concepts of hydroponics are discussed. The book is not highly technical in providing the basics of hydroponics in the initial chapters with regard to plant function and nutrition. The objective is to make the reader aware of the present advances in hydroponics using the various substrates and systems that have proved successful with specific vegetable crops. While most of the material presented relates to greenhouse hydroponic systems, it can be applied to outdoor hydroponic systems under favorable climates. This book is meant to be a practical guide for persons interested in entering hydroponics commercially or as a hobby. Whatever the size of operation the reader may be interested in, the book presents the principles for getting started and gives many examples and illustrations to clarify these methods.

The first four chapters introduce the reader to the history of hydroponics: plant nutrition, essential plant elements, nutrient uptake, nutritional disorders, sources of nutrients including organics, and then a detailed explanation of composing nutrient solutions. Sources of the nutrients are given with conversion tables to facilitate the calculations of nutrients the plant requires to the volumes of nutrient solution makeup. A new section on organic fertilizers has been added exemplifying sources and possible organic nutrient formulations. Concentrated nutrient stock solutions are explained and calculations are clearly exemplified. Many nutrient formulations are given as a reference to start the formulation for specific crops that can be optimized for specific conditions with experience. Various media or substrates most suitable to hydroponics or "soilless culture" are presented to explain their characteristics and assist the reader in choosing the best for his or her specific crop and growing system.

In Chapter 5, water culture systems are explained and illustrated. This includes raft or floating systems on a relatively small scale to large commercial operations. This section contains new material on commercial raceway or raft culture. Information on new commercial green fodder production has been added. Alfalfa and bean sprout production is presented to demonstrate the principles of growing sprouts. Production of microgreens includes both commercial and a do-it-yourself method so that one can easily set up such a system in the residence.

Chapter 6 on nutrient film technique (NFT) expands this culture to the most up-to-date automated systems presently in operation in Europe and North America. This section includes automated baby leaf greens production systems. A new section has been added to the commercial application of an A-frame NFT system growing strawberries in Australia that demonstrates marketing through a restaurant-retail outlet.

Chapters 7 through 9 on gravel, sand, and sawdust cultures, respectively, demonstrate growing systems with irrigation designs.

Chapter 10 on rockwool culture presents commercial state-of-the-art greenhouse operations. Recirculation of the nutrient solution is exemplified with rockwool culture through the use of raised beds. This recirculation of nutrient solution demonstrates the industry is reducing the environmental impact and supports the "green" concept toward the environment. Presented are examples and details of growing the main vine crops of cucumbers, tomatoes, and peppers with rockwool culture. Intercropping of tomatoes in high light regions, such as southern California, Arizona, and Australia are presented.

Chapter 11 on coco coir discusses the sources, grades, and characteristics of coco coir with the available products of cubes, blocks, and slabs that are used in this system. Greenhouse culture is moving toward such sustainable substrates to utilize normal waste products from other industries. Coco coir is such a substrate, similar to the case with sawdust culture in British Columbia, Canada some years ago as illustrated in Chapter 9. Sawdust later was used in manufactured wood products, so now is not readily available. Details of growing tomatoes with coco coir substrate are given.

Chapter 12 is a new chapter to explain the control of environmental factors in greenhouses. It also includes automation in greenhouses to perform daily tasks because of the increasing difficulty of acquiring labor. Temperature control through heating, ventilation and cooling, and polyclima (Ultra Clima, Modulair) systems in sustainable agriculture greenhouse technology are discussed. Combined heat and power (CHP) and cogeneration as part of sustainable greenhouses are presented. Carbon dioxide enrichment principles and generation systems are presented. Relative humidity (RH) and irrigation (fertigation) principles and techniques are given including recirculation of the nutrient solution with components of filtration, sterilization, and injection systems. Lighting principles and sources of lights including high intensity discharge (HID) and LED lighting units are presented.

Computer automation of greenhouse environmental factors and automation of crop production tasks from sowing, transplanting, plant training, harvesting, and packing are reviewed with examples of robotics being tested for crop harvesting. Retractable roof structures for protection of cherries is widely used to get earlier production, to increase yields, facilitate harvesting by new training systems are gaining popularity as the economics are proven. These same structures have advantages over closed greenhouses in tropical, humid climates in Australia, South Africa, Mexico, and the Middle East in growing normal greenhouse crops such as tomatoes, strawberries, lettuce, herbs, and cannabis.

Chapter 13 dealing with other soilless cultures covers the use of rice hulls, peatlite, and perlite cultures. The section on perlite culture has been expanded to elaborate on perlite products such as blocks and slabs and to include culture of eggplants using perlite.

Chapter 14 describing vertical indoor farming (VF) is new. It begins with some background on early vertical greenhouse and sack culture growing systems. From there present vertical growing systems used in greenhouses are described followed by existing commercial vertical greenhouses. Vertical indoor farming reviews many different systems by numerous companies where growing is in large warehouses with tiers of shelving growing lettuce, leafy greens, and herbs under LED lighting. Automation in these vertical farms is presented with each specific system. Vertical growing in containers and/or modular units is discussed. The chapter is summarized by advantages and disadvantages of these vertical farms with final remarks on their potential.

In Chapter 15 new sections have been added on Peru hydroponics describing the work at the Universidad Nacional Agraria La Molina and the large commercial operation of Invernaderos Hidroponias del Peru, near Lima, Peru. “Special Applications” has been updated to include the expansion of hydroponic rooftop greenhouses. New locations are described in New York, Chicago, and Montreal, Canada. Educational applications of hydroponics in school rooftop hydroponic gardens and the public display on the Hudson River in New York of the Science Barge are described.

Plant cultural techniques of Chapter 16 illustrates the training of plants, growing of seedlings, varieties, pest and disease management using integrated pest management (IPM). Eggplant culture is included with these cropping techniques. Green grafting of vine crops is now standard practice for tomatoes, peppers, and eggplants to mitigate crop diseases and increase yields. This is explained in detail using illustrations.

Included in Appendices are websites for all of the hydroponic and greenhouse resources and supplies to make access to them readily available.

Howard M. Resh

Acknowledgments

This book is based on over 43 years of personal working experience, visits with many growers, discussions with researchers and growers at conferences, and participation in many conferences such as the Asociacion Hidroponica Mexicana, A.C.; Centro Nacional de Jardineria Corazon Verde, Costa Rica; Encontro Brasileiro de Hidroponia, Brazil; Greenhouse Crop Production and Engineering Design Short Course, University of Arizona, CEAC; Hydroponic Society of America; International Society of Soilless Culture; and the Research Center for Hydroponics and Mineral Nutrition, Universidad Nacional Agraria, La Molina, Lima, Peru. Much appreciated thanks to the organizers of these conferences including: Gloria Samperio Ruiz, the late Laura Perez, Dr. Pedro Ferlani, Dr. Gene Giacomelli, and Dr. Alfredo Rodriguez Delfin

In addition, some information has been acquired over the years from numerous sources from books, scientific journals, and government publications whose recognition is given in the references following each chapter and in the general bibliography.

Special thanks to Dr. Silvio Velandia of Hidroponias Venezolanas C.A. of Caracas, Venezuela, for the hospitality and inspiration given to me during our association over the years in developing his hydroponic farm. He gave me the opportunity to gain experience in tropical hydroponics and encouraged me to write a chapter about it.

My sincere thanks to George Barile of Accurate Art, Inc. for the art work of the book to give it a unique appearance that adds greatly to its presentation.

Thanks also to the business people who have provided me with the opportunity of developing projects for them. To mention a few: Peter Hoppmann of Hoppmann Corporation, Chantilly, Virginia; Tom Thyer of Environmental Farms, Dundee, Florida; Alfred Beserra of California Watercress, Inc., Fillmore, California; Mohamed Hage, CEO, Lufa Farms, Inc., Montreal, Quebec, Canada; and the late Leandro Rizzuto of CuisinArt Golf Resort & Spa, Anguilla, B.W.I.

Also, a very special thanks to many commercial greenhouse growers who have been very generous in providing me with information on their operations and allowing me to take photographs, many of which appear in this book. To mention a few: Casey Houweling, Houweling's Group, Camarillo, CA; David Bell, CMO, Houweling Management and Marketing Services Canada, Inc., Luc Desrochers, President, Hydronov Inc., Mirabel, Quebec, Canada; Frank van Straalen, Eurofresh Farms, Wilcox, AZ; Chris Millis, COO, Flavorite Group, Warragul, Australia; Anthony Sarks, Ricardoes Tomatoes & Strawberries, Port Macquarie, Australia; Kevin Paulin, Clyde Orchards, Clyde, New Zealand; Miguel Uccelli, Herente General, Invernaderos Hidroponicos del Peru S.A.C., Lima, Peru; Dr. Alfredo Rodriguez Delfin, Director, Centro de Investigacion de Hidroponia, Universidad Nacional Agraria La Molina, Lima, Peru; Steen Nielsen, Gourmet Hydroponics, Inc., Lake Wales, FL.

Others I wish to thank for their cooperation in providing me with photos of their operations and/or products include: Alfonso Aponte, Grupo Tecnico Aponte, Bogota, Colombia; Marilyn Brentlinger and Jeff Balduff, CropKing, Inc., Lodi, OH; Eric Christian, American Hydroponics, Arcata, CA; Kurt Cornelissen, Hortiplan N.V., Belgium; Patrik Borenius, CEO, and Helena Borenius, Marketing and Office Manager, Green Automation Americas LLC, Wellington, FL; Roelof Drost, Jiffy International AS, Norway; Fijtie Eygenraam, FormFlex Horticultural Systems, Beamsville, ON, Canada; Kevin Frediani, Paignton Zoo Environmental Park (Valcent Products Inc.), England; Gordon Graff, Agro-Arcology, Toronto, ON, Canada; Laurie Schoeman, New York Sun Works; Rob Vandersteen, Zwart Systems, Beamsville, ON, Canada; Seven Willems, Willems-Perlite, Belgium; Peter Reus, President, Prins Greenhouses Ltd., Abbotsford, BC, Canada; Richard Vollebregt, President, Cravo Equipment Ltd, Brantford, ON, Canada; Guido van het Hof, President,

Great Northern Hydroponics, Kingsville, ON, Canada; Jenn Frymark, Chief Greenhouse Officer and Jodi Genshaft, VP of Marketing, Gotham Greens, Brooklyn, NY; Brad Holman, Hydronov LLC, Ashley, IN; Amy Prosser, Executive Assistant, Pranger Enterprises, Inc., Ashley, IN; Colin Woodford, GE Current a Daintree Company, Lachine, QC, Canada; Dr. Joshua Lessing, CEO & President, Root AI, Inc., Woburn, MA.

In the writing of Chapter 14 on Indoor Vertical Farms I am grateful for the assistance in providing photos and reviewing of the text to the following: Allison Dupuis, Director of Marketing, Eden Green US & Caribbean Produce Holdings, Inc., Cleburne, TX; Kyra Foley, Marketing Coordinator, Vertical Harvest Farms, Jackson, WY; Roshe Wong, Deputy CEO, Sky Greens Pte Ltd. Singapore; Robert Colangelo, CEO, Green Sense Farms Holdings, Inc., Portage, IN; Marc Oshima, Co-Founder & Chief Marketing Officer and Casey Higgins, Marketing & Design Associate, AeroFarms, Newark, NJ; Rachel Alkon, Bowery Farming Inc., New York, NY; Eric Lang, President, Ian Friderich, Account Executive, and Gina Scandrett, ZipGrow, Inc., Cornwall, ON, Canada; Nate Storey, Chief Science Officer and Jane Gideon, VP Communications, Plenty Inc., San Francisco, CA: Omar Al Jundi, CEO, and Lia Hapsari, Office Manager/Executive Assistant, Badia Al Sahra Agriculture LLC, Badia Farms, Dubai, UAE; Phil Gibson, Vice President of Marketing, AEssenseGrows, Sunnyvale, CA; Ali Amirlatifi, CEO, Evergreen Farm Oy, Tampere, Finland; Rebecca Shamritsky, Marketing Manager at Freight Farms, Boston, MA; Brecht Stubbe, Global Sales Director and Doug Gamble, North American Sales Manager, Urban Crop Solutions BV, Waregem, Belgium and Miami, FL; Jordan Dinesen, Business Development & Marketing, Andrea Magee, Communications Manager, and Sandy Gerber, VP of Marketing, Cubic Farms, Langely, BC, Canada.

Many thanks also to Chris Higgins of Hort Americas for the assistance in providing contacts in many of these industries.

My sincere gratitude to all of these people who are furthering the advances of hydroponics in greenhouse and indoor farming technologies.

In no way is the use of trade names intended to imply approval of any particular source or brand name over other similar ones not mentioned in this book.

–The Author

Author Bio

Howard M. Resh (born January 11, 1941) is a recognized authority worldwide on hydroponics. His website: www.howardresh.com presents information on hydroponic culture of various vegetable crops. In addition, he has written six books on hydroponic culture both for commercial growers and backyard hobbyists. While a graduate student at the University of British Columbia, in Vancouver, Canada in 1971, he was asked by a private group to assist them in the construction of hydroponic greenhouses in the Vancouver area. He continued with outside work in greenhouses and soon was asked to conduct evening extension courses in hydroponics.

Upon graduation with his doctorate degree in Horticulture in 1975 he became Urban Horticulturist for the faculty of plant science at the University of B.C. He held that position for three years before the call of commercial hydroponics took him to many projects in countries such as Venezuela, Taiwan, Saudi Arabia, the United States, and in 1999 to Anguilla, British West Indies, in the Eastern Caribbean.

While in the position of urban horticulturist, Resh taught courses in horticulture, hydroponics, plant propagation, greenhouse design, and production. During this period, while he was urban horticulturist and later general manager for a large plant nursery, he continued doing research and production consultation for a commercial hydroponic farm growing lettuce, watercress, and other vegetables in Venezuela. Later, during the period 1995–1996, Resh became project manager for the Venezuelan farm to develop hydroponic culture of lettuce, watercress, peppers, tomatoes, and European cucumbers using a special medium of rice hulls and coco coir from local sources. He also designed and constructed a mung bean and alfalfa sprout facility to introduce sprouts into the local market.

In the late 1980s, Resh worked with a company in Florida in the growing of lettuce in a floating raft culture system.

From 1990 to 1999, Resh worked as the technical director and project manager for hydroponic projects in the growing of watercress and herbs in California. He designed and constructed several 3-acre outdoor hydroponic watercress facilities using a unique NFT system. These overcame production losses due to drought conditions in the area.

From there in mid-1999, Resh became the hydroponic greenhouse farm manager for the first hydroponic farm associated with a high-end resort, CuisinArt Golf Resort & Spa, in Anguilla, British West Indies in the northeastern Caribbean. The hydroponic farm is unique in being the only one in the world owned by a resort growing its own fresh salad crops and herbs exclusively for the resort. This farm has become a key component of the resort in attracting guests to experience real homegrown types of vegetables, including tomatoes, cucumbers, peppers, eggplants, lettuce, bok choy, and herbs. The resort, together with its hydroponic farm, has gained world-wide recognition as one of the leading hotels of the world.

Resh continues to do consulting on many unique hydroponic greenhouse operations such as Lufa Farms in Montreal, Canada. There he established the growing techniques and hydroponic systems for a rooftop hydroponic greenhouse in downtown Montreal. All vegetables are marketed through a community supported agriculture (CSA) program.

In 2016, Resh retired from full-time work at CuisinArt Golf Resort & Spa and now independently consults with a number of companies including work on indoor vertical farming.

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1 Introduction

1.1 THE PAST

While hydroponics is a fairly recent term for growing plants without soil, the method dates back much earlier. The hanging gardens of Babylon, the floating gardens of the Aztecs of Mexico, and those of the Chinese were a form of "hydroponic" culture, although not referred to as that. Even Egyptian hieroglyphic records of several hundred years B.C. describe the growing of plants in water. Theophrastus (372–287 B.C.) undertook various experiments in crop nutrition. Botanical studies by Dioscorides date back to the first century A.D.

The earliest recorded scientific approach to discover plant constituents was in 1600 when Belgian Jan van Helmont showed in his classical experiment that plants obtain substances from water. While his conclusion that plants obtain substances for growth from water was correct, he failed to realize that they also require carbon dioxide and oxygen from the air. In 1699, an Englishman, John Woodward, grew plants in water containing various types of soil and found that the greatest growth occurred in water which contained the most soil. He thereby concluded that plant growth was a result of certain substances in the water, derived from soil, rather than simply from water itself.

Further progress in identifying these substances was slow until more sophisticated research techniques were developed and advances were made in the field of chemistry. In 1804, De Saussure proposed that plants are composed of chemical elements obtained from water, soil, and air. This proposition was verified later in 1851 by Boussingault, a French chemist, in his experiments with plants grown in sand, quartz, and charcoal, to which were added solutions of known chemical composition. He concluded that water was essential for plant growth in providing hydrogen and that plant dry matter consisted of hydrogen plus carbon and oxygen, which came from the air. He also stated that plants contain nitrogen and other mineral elements.

Researchers had demonstrated by that time that plants could be grown in an inert medium moistened with a water solution containing minerals required by the plants. The next step was to eliminate the medium entirely and grow the plants in a water solution containing these minerals. This was accomplished in 1860–1861 by two German scientists, Sachs and Knop. This was the origin of "nutriculture," and similar techniques are still used today in laboratory studies of plant physiology and plant nutrition. These early investigations in plant nutrition demonstrated that normal plant growth can be achieved by immersing the roots of a plant in a water solution containing salts of nitrogen (N), phosphorus (P), sulfur (S), potassium (K), calcium (Ca), and magnesium (Mg), which are now defined as the macroelements or macronutrients (elements required in relatively large amounts).

With further refinements in laboratory techniques and chemistry, scientists discovered seven elements required by plants in relatively small quantities – the microelements or trace elements. These include iron (Fe), chlorine (Cl), manganese (Mn), boron (B), zinc (Zn), copper (Cu), and molybdenum (Mo).

In the following years, researchers developed many diverse basic formulae for the study of plant nutrition. Some of these workers were Arnon, Hoagland, Robbins, Shive, Tollens, Tottingham, and Trelease. Many of their formulae are still used in laboratory research on plant nutrition and physiology.

Interest in practical application of this "nutriculture" did not develop until about 1925 when the greenhouse industry expressed interest in its use. Greenhouse soils had to be replaced frequently to overcome problems of soil structure, fertility, and pests. As a result, research workers became aware of the potential use of nutriculture to replace conventional soil cultural methods. Between 1925 and

DOI: 10.1201/9781003133254-1

1935, extensive development took place in modifying the laboratory techniques of nutriculture to large-scale crop production.

In the early 1930s, W.F. Gericke of the University of California put laboratory experiments in plant nutrition on a commercial scale. In doing so, he termed these nutriculture systems *hydroponics.* The word was derived from two Greek words – *hydro* ("water") and *ponos* ("labor") – literally "water working."

Hydroponics can be defined as the science of growing plants without the use of soil, but by the use of an inert medium, such as gravel, sand, peat, vermiculite, pumice, perlite, coco coir, sawdust, rice hulls, or other substrates, to which is added a nutrient solution containing all the essential elements needed by the plant for its normal growth and development. Since many hydroponic methods employ some type of medium it is often termed "*soilless culture*," while water culture alone would be true hydroponics.

Using hydroponics, Gericke grew vegetables, including root crops such as beets, radishes, carrots, and potatoes; cereal crops; fruits; ornamentals; and flowers. Using water culture in large tanks, he grew tomatoes to such heights that he had to harvest them with a ladder. The American press made many irrational claims, calling it the discovery of the century. After an unsettled period in which unscrupulous people tried to cash in on the idea by selling useless equipment, more practical research was done and hydroponics became established on a sound scientific basis in horticulture, with recognition of its two principal advantages, high crop yields and its special utility in nonarable regions of the world.

Gericke's application of hydroponics soon proved itself by providing food for troops stationed on nonarable islands in the Pacific in the early 1940s. In 1945, the US Air Force solved its problem of providing its personnel with fresh vegetables by practicing hydroponics on a large scale on the rocky islands normally incapable of producing such crops.

After World War II, the military command continued to use hydroponics. For example, the US Army established a 22-ha project at Chofu, Japan. The commercial use of hydroponics expanded throughout the world in the 1950s to such countries as Italy, Spain, France, England, Germany, Sweden, the USSR, and Israel.

1.2 THE PRESENT

With the development of plastics, hydroponics took another large step forward. Plastics freed growers from the costly construction associated with the concrete beds and tanks previously used. With the development of suitable pumps, time clocks, plastic plumbing, solenoid valves, and other equipment, the entire hydroponic system can now be computer automated, reducing both capital and operational costs. Many modern greenhouse operations now use automation in the moving of growing channels within the greenhouse and automated, robotic transplanting and harvesting. Such operations exist in Europe and the United States. Hortiplan is such a company from Belgium that engineers and manufactures nutrient film technique (NFT) water-culture systems for automation, used at present in Belgium, Holland, the United States, and other areas of the world. Similar moving gutter systems (MGS) are available from several other companies, such as Viemose DGS of Denmark and Green Automation of Finland. These systems are elaborated upon in Chapter 6.

Hydroponics has become a reality for greenhouse growers in virtually all climates. Large hydroponic installations exist throughout the world for the growing of both flowers and vegetables. Many hydroponic vegetable production greenhouses exist in the United States, Canada, and Mexico that are 50 acres or larger in area. Large US growers include Village Farms, L.P., with operations (seven partner growers) in Western Canada, with the majority in Delta, British Columbia (60 acres), and Fort Davis and Marfa, Texas (40 acres). They have six partner growers in Mexico and two partner growers in Pennsylvania, with a total of 315 acres. Kentucky-based AppHarvest has 60 acres of greenhouse production in Morehead, Kentucky. Houweling's Group has 130 acres of greenhouse production in California and 28 acres in Utah (expanding by 30 acres in 2021). In Canada greenhouses

larger than 50 acres include Houweling's Group, Delta, British Columbia; Windset Farms, Delta, British Columbia. Mastron Enterprises Ltd., Leamington, Ontario; Nature Fresh Farms, Leamington, Ontario; Pure Hothouse Foods Inc., Leamington, Ontario; and DiCiocco Farms, Leamington, Ontario; Great Northern Hydroponics, Leamington, Ontario; and Mucci Farms of Kingsville, Ontario.

1.2.1 North American Greenhouse Vegetable Industry

The following statistics indicate the expansion of the North American greenhouse vegetable industry. A similar growth has occurred in Europe, but here the focus is on North America. In 1998 the industry in British Columbia (B.C.) and Ontario, Canada was reported at 1140 acres (456 ha). The Ontario marketing board claimed that in 1999 there was more than 800 acres (320 ha) of greenhouse vegetables compared to 600 acres (240 ha) the previous year. In 1998 the British Columbia Ministry of Agriculture and Lands reported 310 acres (124 ha) of greenhouse vegetable production. This increased over the next four years by 2002 to 510 acres (204 ha). Statistics Canada reported for 2008 and 2009 respectively; there were 2775 acres (1110 ha) and 2852 acres (1141 ha).

The Government of Canada 2018 Statistical Overview of the Canadian Greenhouse Vegetable Industry reported 1735 ha (4285 acres) in Canada with the largest areas in Ontario and British Columbia at 1220 ha (3013 acres) and 314 ha (775 acres) respectively. Perhaps, the small increase in B.C. is due to some of the large operations, such as Village Farms having converted 10 ha (25 acres) of their vegetable production to cannabis growing in 2017.

The breakdown of Canada's hydroponic greenhouse vegetable production according to 2018 data from Agriculture and Agri-Food Canada is as follows: Tomato-659 ha (1628 acres); Pepper-561 ha (1386 acres); Cucumber-457 ha (1128 acres); Lettuce-22 ha (54 acres); Eggplants-11 ha (27 acres); Herbs and other vegetables-25 ha (62 acres) totaling 1736 ha or 4285 acres. These figures are broken down into the area per crop in Table 1.1.

Hydroponic (soilless) culture is used in growing the majority of greenhouse ornamentals. In North America (Canada, US, and Mexico) the average percentage of ornamental compared to vegetable greenhouse crops is 63% vs. 37% (Hickman, 2018) indicating that the area of hydroponic greenhouse growing is much larger than what is presented here for vegetables alone. The percentage of hydroponic ornamentals is even greater in other countries such as the Netherlands.

The latest figures for the US greenhouse area in 2017 were given by the US Census of Agriculture, 2017. Total greenhouse vegetable production was 1046 ha (2584 acres). Of this total, the area of tomatoes was 594 ha (1468 acres). There was no breakdown for the other crops. In 2015 greenhouse vegetable production in Mexico was 3676 ha (9084 acres) as published in *International Greenhouse Vegetable Production Statistics – 2018 Edition* by Gary W. Hickman. The total North American greenhouse vegetable production was reported to be 6396 ha or 15,883 acres.

Almost half of the greenhouse vegetable production area in the US is produced by ten companies. They have 435 ha (1078 acres) of the total production of 1046 ha (2584 acres) as reported in 2017. That is, they operate 42% of the greenhouse area in the US. The following is a list of these large greenhouse operations.

Nature Sweet (Desert Glory Ltd.) – 106 ha (262 acres) (AZ) (2017)
Winset Farms – 68 ha (168 acres) (CA) (2020)
Houweling's Group – 50 ha (124 acres) (CA) + 23 ha (58 acres) (UT) (2021)
Village Farms – 49 ha (122 acres) + 12 ha (30 acres) (TX) (2020)
Sunblest Farms – 36 ha (90 acres) (CO) (2000)
Intergrow – 38.5 ha (95 acres) (NY) (2019)
AppHarvest – 24.3 ha (60 acres) (KY) (2021)
Mastronardi Produce (Backyard Farms) – 17 ha (42 acres) (ME) (2017)
Mucci Farms – 20 ha (50 acres) (OH) (2020)
Nature Fresh Farms – 18 ha (45 acres) (OH) (2018)

TABLE 1.1
Greenhouse Vegetable Production Area, Canada 2017–2019

Province	Tomatoes Hectares (Acres)	Cucumbers Hectares (Acres)	Peppers Hectares (Acres)	Lettuce Hectares (Acres)	Eggplants Hectares (Acres)	Herbs Hectares (Acres)	*Other Hectares (Acres)	Totals Hectares (Acres)
				2017:				
British Columbia	108 (267)	44 (109)	155 (383)	4.3 (10.5)	1.5 (3.7)	6.3 (15.6)	2.9 (7.2)	322 (795)
Ontario	436 (1077)	322 (795)	395 (976)	4.5 (11)	8.3 (20.5)	0.3 (0.74)	2.2 (5.4)	1168 (2885)
Others	92 (227)	66 (163)	13 (32)	12 (30)	1.2 (3)	2.6 (6.4)	9 (22.2)	196 (484)
Canada	636 (1571)	432 (1067)	563 (1391)	21 (52)	11 (27)	9.1 (22.7)	14.1 (34.8)	1686 (4164)
				2018:				
British Columbia	104 (257)	45 (111)	148 (365)	5 (12)	1.4 (3.4)	4.2 (10.4)	6 (14.8)	314 (775)
Ontario	460 (1136)	343 (847)	400 (988)	5 (12)	8.7 (21.4)	0.34 (0.84)	2.9 (7.2)	1220 (3013)
Others	95 (235)	69 (170)	13 (34)	12 (30)	0.9 (2.2)	2.5 (6.2)	8.8 (21.7)	201 (497)
Canada	659 (1628)	457 (1128)	561 (1386)	22 (54)	11 (27)	7 (18)	17.7 (44)	1736 (4285)
				2019:				
British Columbia	96.3 (238)	45.7 (113)	144 (356)	5.4 (13)	1.2 (3)	7.6 (19)	2.8 (7)	303 (749)
Ontario	456 (1126)	368 (909)	399 (986)	6.7 (16.5)	8.4 (21)	0.4 (1)	1.1 (2.7)	1240 (3062)
Others	94 (232)	70.4 (174)	14 (34.5)	19.6 (48.4)	1.1 (2.7)	2.5 (6.2)	10.5 (26)	212 (524)
Canada	646.3 (1596)	484 (1196)	557 (1376)	31.7 (78)	10.7 (26.7)	10.5 (26.2)	14.4 (36)	1755 (4335)

*Other: Other Greenhouse Vegetable Crops – Chinese vegetables and leafy greens.

Source: Statistics Canada. Table 32-10-0456-01 Production and value of greenhouse vegetables

1.2.2 World Greenhouse Vegetable Industry

While there are many statistics reporting areas of greenhouse vegetable production throughout the world, it is important to recognize that often such statistics include all protective structures, such as high plastic tunnels, shade structures, and any structures that will extend the growing season of plants. Many of these are not greenhouses with environmental control systems such as heating, cooling, nutrient systems with drip irrigation, protection against pests, and other components to modify the internal environment to achieve optimal conditions for the crop grown. In addition, greenhouses in many countries may still use soil and not a soilless or hydroponic system.

A recent publication by Gary W. Hickman, *International Greenhouse Vegetable Production Statistics – 2018 Edition*, claims world soilless/hydroponic vegetable production is about 95,000 ha (235,000 acres). Hickman also points out that commercial greenhouse vegetable production is estimated at 498,000 ha (1.23 million acres).

Greenhouse hydroponic production must be considered as using a hydroponic system, not just covering the existing soil with a very lightweight poly structure such as poly tunnels and plastic low tunnels and applying water with some nutrients by a drip irrigation system, such as in areas like the Canary Islands, Spain, China, and Mexico. For example, Hickman points out that Mexico is producing about 3770 ha (9300 acres) of natural ventilated, unheated, high-tunnel structures of plastic covered metal structures with insect sidewalls. These "greenhouses" often have computerized irrigation and fertilization systems, but are growing in the local soil. As a result, they cannot be termed "hydroponic."

The largest Mexican hydroponic greenhouse operation is Bionatur Greenhouses in Jocotitlan, Mexico. They operate 200 acres or 80 ha growing tomatoes with 1000 employees. There are numerous other hydroponic greenhouse vegetable production facilities, such as Agros S.A. presently 17 ha or 42 acres in the state of Queretaro.

Holland, on the other hand, has 4865 ha (12,022 acres) of hydroponic vegetable production with sophisticated, high-technology greenhouses of metal and glass with computer-controlled environments. Other statistics report an area of 10,000 ha (25,000 acres), but that would include flower production. While Holland is still the largest, Spain now has about 4000 ha; however, the greenhouse structures there are much lower-cost polyethylene structures unlike most Dutch glass greenhouses. Belgium in 2007 had about 1430 ha (3530 acres). Germany in 2015 had about 1204 ha or 2975 acres according to statistics gathered by Hickman.

Further statistics presented by Hickman (2019) indicate in 2016 Australia greenhouse production was 500 ha (1230 Ac). NFT, rockwool and coco coir cultures are the principal hydroponic methods employed. The greater portion of hydroponic growers is located in New South Wales and Victoria.

Nichols and Christie (2008) reported in *Practical Hydroponics & Greenhouses* that, in 2007 Japan had 52,000 ha of greenhouses, mainly of plastic, with only 5% glass, but only 1500 ha (3%) were in a hydroponic system.

The largest growers in Australia include Costa Tomatoes in Guyra, NSW, with 30.2 ha (75 acres) presently expanding to 40 ha (99 acres). In Two Wells, near Adelaide, South Australia, d'VineRipe is located, which has 43 ha (106 acres). Flavorite in Warragul, Victoria, has 26 ha (64 acres), presently expanding by 4.5 ha (11 acres) for a total of 30.5 ha (75 acres). Sundrop Farms in Port Augusta, South Australia, has a 20-hectare (50-acre) greenhouse using a solar tower to produce energy for the greenhouse operation. These greenhouses grow principally tomatoes and peppers.

The largest greenhouse operation in New Zealand is NZ Hothouse, Drury, near Auckland. They have 20 ha (~50 acres) of Venlo glasshouses growing mainly tomatoes with some cucumbers in rockwool. They supply New Zealand supermarkets and export to Canada, the United States, Australia, Singapore, Japan, Taiwan, and Oceania.

Hydroponics is now used in almost every country in the world. Hickman, in his study of greenhouse vegetable production, reported information on 130 countries that produce greenhouse vegetables commercially. While the majority of this greenhouse vegetable production is in the soil, hydroponics is generally also part of this industry, even if on a smaller scale. Even countries such as Turkey in 2014 claim 65,000 ha (160,500 acres) of greenhouse production. As mentioned earlier, such as in the case of Spain and Mexico, a large part of that production would be in plastic tunnels and low-profile cold frames that may be misnamed greenhouses. Hickman (2019) reported almost 30,000 ha (74,100 acres) of this was plastic greenhouses with 8114 ha (20,042 acres) glass greenhouses. Their principal production is tomatoes, cucumbers, peppers, watermelons, and eggplants.

Greenhouse vegetable area in Russia, from statistics reported by Hickman (2018), had increased from 1840 ha (4547 acres) in 2012 to 2931 ha (7243 acres) in 2014.

TABLE 1.2
Large World Greenhouse Vegetable Operations

Country	Name	Hectares	Acres
Morocco	Group Azura	751	1856
Mexico	Desert Glory	405	1000
Mexico	Melones	350	865
China	Le Gaga	263	649
Mexico	Agricola la Primavera	162	400
Russia	Yuzhny	148	366
Canada	Petro Veg. Co.	135	334
Mexico	Divemex	135	334
Mexico	Bioparques de Occidente	130	321
Russia	Agrikombinat Moskovsky	120	300
Mexico	Grupo Batiz-Wilson Batiz	115	284
USA	Nature Sweet Arizona	106	265
Netherlands	Royal Pride	102	252
Israel	Gilad Desert Produce	100	250

In arid regions of the world, such as Mexico and the Middle East, hydroponic complexes combined with desalination units are being developed to use sea water as a source of fresh water. With less expensive desalination equipment, such as reverse osmosis (RO), water can be generated in these arid regions at an economically feasible cost for use in greenhouses. The complexes are located near the ocean and plants are often grown in the existing sand.

Global Greenhouse Vegetable Area-*By Continent 2017 (Compiled by Hickman, 2018)*

Europe	173,561 ha. (428,879 acres)
South America	12,502 ha. (30,893 acres)
North America	7,288 ha. (18,009 acres)
Asia	224,974 ha. (555,923 acres)
Africa	36,993 ha. (91,412 acres)
Oceania	2,036 ha. (5,031 acres)

Large world greenhouse vegetable operations (Table 1.2) are from numerous sources that were compiled by Hickman (2018).

This list of the largest greenhouse operations in the world may not all use hydroponic culture. Desert Glory, Petro Veg. Co., and Nature Sweet Farms use only hydroponic culture. The following list in Table 1.3 is the area of soilless or hydroponic culture in greenhouses in some countries.

1.3 THE FUTURE

In a relatively short period of time, over about 65 years, hydroponics has adapted to many situations, from outdoor field culture and indoor greenhouse culture to highly specialized culture in the space program. It is a space-age science, but at the same time can be used in developing countries of the Third World to provide intensive food production in limited area. Its only restraints are sources of fresh water and nutrients. In areas where fresh water is not available, hydroponics can use seawater through desalination. Therefore, it has potential application in providing food in areas having vast regions of nonarable land, such as deserts. Hydroponic operations can be located along coastal

TABLE 1.3
Soilless/Hydroponic Greenhouse Vegetable Production Area

Country	Hectares	Acres	
China	1,250	3,100	
Japan	1,500	3,700	
Turkey	500	1,235	
Italy	4,000	10,000	
Morocco	426	1,053	
Netherlands	4,600	11,300	(some area is not soilless)
Mexico	4,305	10,638	(some area is not soilless)
New Zealand	688	1,700	(95% is soilless culture)
U.S.A.	574	1,418	
United Kingdom	89	220	
South Africa	75	185	
Taiwan	35	86	
Singapore	30	74	
Canada	1,141	2,852	

Source: Gary W. Hickman, 2011, *Greenhouse Vegetable Production Statistics.*

regions in combination with petroleum-fueled, solar, or atomic desalination units, using the beach sand as the medium for growing the plants.

Hydroponics is a valuable culture to grow fresh vegetables in countries having little arable land and those that are very small in area yet have a large population. It could also be particularly useful in some smaller countries whose chief industry is tourism.

In such countries tourist facilities, such as resort hotels, can grow their own products instead of importing them many thousands of miles away, with long shipping periods. Typical examples of such regions are the West Indies and Hawaii, which have a large tourist industry and very little farm land in vegetable production.

Hydroponic greenhouse operations will be linked with industries having waste heat or alternative sources of energy. Such cogeneration projects already exist in California, Colorado, Nevada, Pennsylvania, and Utah. Anaerobic digesters of animal waste products can have hydroponic greenhouses associated with them in the Midwest where lots of dairy farms exist. The anaerobic digesters can generate heat and electricity. Electric power generating stations use water in their cooling towers. This heated water can be used both for heating the greenhouse and providing distilled water free of minerals for the growing of plants in recirculation systems. This clean water is of particular advantage to growers in areas normally having hard raw water. In most of the sun-belt locations where sunlight is favorable to high production of vegetables, waters are very hard with high levels of minerals, which are often in excess of normal plant requirements. The hard water also creates problems with corrosion of equipment, plugging of cooling pads, fogging systems, and structural breakdown of growing media.

With the introduction of new technology in artificial lighting, the growing of plants using artificial lighting will become economically feasible, especially in the more northern latitudes where sunlight is limited during the year, from late fall to early spring. During this period, of course, the prices for produce are much higher than in summer months. The new LED lights have this potential. Heat generated from the lights could be used to supplement the heating of the growing operation.

There are many locations in western North America having geothermal sources of heat. Such sites exist in Alaska, California, Colorado, Idaho, Montana, Oregon, Utah, Washington, Wyoming,

and British Columbia. In the future, large greenhouses should be located close to geothermal sites to utilize the heat, as is presently done in Hokkaido, Japan.

At present, a lot of research is being carried out to develop hydroponic systems for the growing of vegetables on the space station. Closed-loop recirculation systems are being designed and tested to operate under microgravity (very low gravity) environments. Such hydroponic systems will grow food to nourish astronauts on long space missions.

In large cities where fresh vegetables are transported often long distances from their growing facilities, there is potential for hydroponic greenhouse roof-top gardens. In a recent issue of *Scientific American* (November 2009), an article was written by Despommier (2009) describing how vertical high-rise buildings of 30 stories could grow produce within our large cities. Hydroponic systems would be used in conjunction with solar cells and incineration of plant waste to create power, and treated wastewater from the city would irrigate the plants. Sunlight and artificial lighting would provide light.

The most recent commercial development over the past ten years is the growing of commercial vegetable crops in *Indoor Vertical Farms* (VF). This is being termed the future of vegetable production within large cities or nearby in urban areas. These VFs now exist in North America, Europe, Middle East, Southeast Asia, Japan, Taiwan, and China. Vertical farms are discussed in Chapter 14.

1.4 SUITABLE SITE CHARACTERISTICS

When considering a hydroponic greenhouse site location, try to meet as many of the following requirements as possible to improve success.

1. In northern latitudes, a site that has full east, south, and west exposure to sunlight with a windbreak on the north.
2. An area that is as near level as possible or one that can be easily leveled.
3. Good internal drainage with minimum percolation rate of 1 in./h.
4. Availability of natural gas, three-phase electricity, telephone, and good-quality water, with capability to supply at least one-half gallon of water per plant per day. If the raw water is high in salts, an RO desalination unit will be needed.
5. Location on or near a main road close to a population center for wholesale market and retail market at the greenhouses if one chooses to sell retail.
6. Location close to residence for ease of checking the greenhouse during extremes of weather. All modern computer-controlled greenhouses have alarm and call-up systems to alert the grower. Parameters can also be checked through a laptop computer or mobile phone.
7. North–south oriented greenhouses with rows also north–south in northern latitudes.
8. A region that has a maximum amount of sunlight.
9. Areas not having excessive strong winds.
10. Areas that are not of high water table or in a flood plain. Fill would be required in such areas, which will add to capital costs.

1.5 SOIL VERSUS SOILLESS CULTURE

The large increases in yields under hydroponic culture over that of soil may be due to several factors. In some cases, the soil may lack nutrients and have poor structure; therefore, soilless culture would be very beneficial. The presence of pests or diseases in the soils greatly reduces overall production. Under greenhouse conditions, when environmental conditions other than the medium are similar for both soil and soilless culture, the increased production of tomatoes grown hydroponically is usually

TABLE 1.4
Advantages of Soilless Culture versus Soil Culture

Cultural Practice	Soil Culture	Soilless Culture
Sterilization of growing medium	Steam, chemical fumigants; labor intensive; time required is lengthy; minimum 2–3 wk	Steam, chemical fumigants with some systems; others can use bleach or HCl; short time needed to sterilize
Plant nutrition	Highly variable, localized deficiencies: often unavailable to plants because of poor soil structure or *p*H; unstable conditions; difficult to sample, test, and adjust	Controlled; relatively stable; homogeneous to all plants; readily available in sufficient quantities; good control of *p*H; easily tested, sampled, and adjusted
Plant spacing	Limited by soil nutrition and available light	Limited only by available light; making closer spacing possible; increased number of plants per unit area, resulting in more efficient use of space and greater yields per unit area
Weed control cultivation	Weeds present, cultivate regularly	No weeds, no cultivation
Diseases and soil inhabitants	Many soil-borne diseases, nematodes, insects, and animals, which can attack crops; frequent use of crop rotation to overcome buildup of infestation	No diseases, insects, animals in medium; no need for crop rotation
Water	Plants often subjected to water stress because of poor soil-water relations, soil structure, and low water-holding capacity. Saline waters cannot be used. Inefficient use of water; much is lost as deep percolation past the plant root zone and also by evaporation from the soil surface	No water stress. Complete automation by use of moisture-sensing devices and a feedback mechanism. Reduces labor costs, can use relatively high saline waters, efficient water use, no loss of water to percolation beyond root zone or surface evaporation; if managed properly, water loss should equal transpirational loss
Fruit quality	Often fruit is soft or puffy because of potassium and calcium deficiencies. This results in poor shelf life	Fruit is firm, with long shelf life. This enables growers to pick vine-ripened fruit and ship it long distances. In addition, little, if any, spoilage occurs at the supermarket. Some tests have shown higher Vitamin A content in hydroponically grown tomatoes than in those grown in soil
Fertilizers	Use large quantities over the soil, nonuniform distribution to plants, large amount leached past plant root zone (50–80%), inefficient use	Use small quantities, uniformly distributed to all plants, no leaching beyond root zone, efficient use
Sanitation	Organic wastes used as fertilizers onto edible portions of plants cause many human diseases	No biological agents added to nutrients; no human disease organisms present on plants

(*continued*)

TABLE 1.4 (Continued)
Advantages of Soilless Culture versus Soil Culture

Cultural Practice	Soil Culture	Soilless Culture
Transplanting	Need to prepare soil, uproot plants, which leads to transplanting shock. Difficult to control soil temperatures and disease organisms, which may retard or kill transplants	No preparation of medium required before transplanting; transplanting shock minimized, faster "take" and subsequent growth. Medium temperature can be maintained optimum. No disease present
Plant maturity	Often slowed by non-optimum conditions	With adequate light conditions, plant can mature faster under a soilless system than in soil
Permanence	Soil in a greenhouse must be changed regularly every several years since fertility and structure break down	No need to change medium in gravel, sand, or water cultures; no need to fallow. Sawdust, peat, coco coir, vermiculite, perlite, rockwool may last for several years between changes with sterilization
Yields	Greenhouse tomatoes 15–20 lb/yr/plant	Greenhouse tomatoes 50–70 lb/yr/plant

20–25%. Such greenhouses practice soil sterilization and use adequate fertilizers; as a result, many of the problems encountered under field conditions in soil would be overcome. This would account for the smaller increases in yields obtained by soilless culture under greenhouse conditions over the very striking 4–10 times increase in yields obtained by soilless culture outdoors over conventional soil-grown conditions.

Specific greenhouse varieties have been bred to produce higher yields under greenhouse culture than field-grown varieties could under the same conditions. These greenhouse varieties cannot tolerate the daily temperature fluctuations of outdoor culture; therefore, their use is restricted to greenhouse growing. Nonetheless, given optimum growing conditions of hydroponic greenhouse culture, they will far out-yield field varieties. The principal vegetable crops grown in hydroponic greenhouse culture include tomatoes, cucumbers, peppers, eggplants, lettuce and other leafy greens and herbs.

These greenhouse varieties have also been bred to resist or tolerate diseases of the foliage and roots, thereby increasing production. Now rootstocks are green grafted to tomatoes, peppers, and eggplants. The tomato root stock is more vigorous than the scion (commercial variety) and resists root diseases.

The main disadvantages of hydroponics are the high initial capital cost; some diseases caused by organisms such as *Fusarium* and *Verticillium*, which can spread rapidly through the system; and the complex nutritional problems encountered. Most of these disadvantages can be overcome by rootstocks, new varieties having more disease resistance, and better nutrient testing, devices.

Overall, the main advantages of hydroponics over soil culture are more efficient nutrition regulation, availability in regions of the world having nonarable land, efficient use of water and fertilizers, ease and low cost of sterilization of the medium, and higher-density planting, leading to increased yields per acre (Table 1.4).

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2 Plant Nutrition

2.1 PLANT CONSTITUENTS

The composition of fresh plant matter includes about 80–95% water. The exact percentage of water depends on the plant species and the turgidity of the plant at the time of sampling, which is a result of the time of day, amount of available moisture in the soil, temperature, wind velocity, and other factors. Because of the variability in fresh weight, chemical analyses of plant matter are usually based on the more stable dry matter. Fresh plant material is dried at 70°C for 24–48 h. The dry matter remaining constitutes roughly 10–20% of the initial fresh weight. Over 90% of the dry weight of most plant matter consists of the three elements: carbon (C), oxygen (O), and hydrogen (H). Water supplies hydrogen and oxygen. Oxygen also comes from carbon dioxide from the atmosphere, as does carbon.

If only 15% of the fresh weight of a plant is dry matter, and 90% of this is represented by carbon, oxygen, and hydrogen, then all the remaining elements in the plant account for roughly 1.5% of the fresh weight of the plant (0.15 x 0.10 = 0.015).

2.2 MINERAL AND ESSENTIAL ELEMENTS

While a total of 92 natural mineral elements are known, only 60 elements have been found in various plants. Although many of these elements are not considered essential for plant growth, plant roots probably absorb to some extent from the surrounding soil solution any element existing in a soluble form. However, plants do have some ability to select the rate at which they absorb various ions, so absorption is usually not in direct proportionate to nutrient availability. Furthermore, different species vary in their ability to select particular ions.

An element must meet each of three criteria to be considered essential to plant growth (Arnon and Stout, 1939; Arnon, 1950; 1951): (1) the plant cannot complete its life cycle in the absence of the element; (2) action of the element must be specific; no other element can wholly substitute for it; and (3) the element must be directly involved in the nutrition of the plant, that is, be a constituent of an essential metabolite or, at least, be required for the action of an essential enzyme, and not simply cause some other element to be more readily available or antagonize a toxic effect of another element.

Only 16 elements are generally considered to be essential for growth of higher plants. They are arbitrarily divided into the macronutrients (macroelements), those required in relatively large quantities, and the micronutrients (trace or minor elements), those needed in considerably smaller quantities.

Macroelements include carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulfur (S), and magnesium (Mg). Microelements include iron (Fe), chlorine (Cl), manganese (Mn), boron (B), zinc (Zn), copper (Cu), and molybdenum (Mo). The relative concentrations of these elements found in most higher plants are given in Table 2.1.

Although most higher plants require only the 16 essential elements, certain species may need others. They may, at least, accumulate these other elements even if they are not essential to their normal growth. Silicon (Si), nickel (Ni), aluminum (Al), cobalt (Co), vanadium (V), selenium (Se), and platinum (Pt) are a few of these elements absorbed by plants and used in their growth. Cobalt is used by legumes for N_2 fixation. Nickel is now believed to be an essential element. It is essential for

DOI: 10.1201/9781003133254-2

TABLE 2.1
Elements Essential for Most Higher Plants

Element	Symbol	Available Form	Atomic Weight	Parts per Million (ppm)	Concentration in Dry Tissue %
		Macronutrients			
Hydrogen	H	H_2O	1.01	60,000	6
Carbon	C	CO_2	12.01	450,000	45
Oxygen	O	O_2, H_2O	16.00	450,000	45
Nitrogen	N	NO_3^-, NH_4^+	14.01	15,000	1.5
Potassium	K	K^+	39.10	10,000	1.0
Calcium	Ca	Ca^{2+}	40.08	5,000	0.5
Magnesium	Mg	Mg^{2+}	24.32	2,000	0.2
Phosphorus	P	$H_2PO_4^-$, HPO_4^{2-}	30.98	2,000	0.2
Sulfur	S	SO_4^{2-}	32.07	1,000	0.1
		Micronutrients			
Chlorine	Cl	Cl^-	35.46	100	0.01
Iron	Fe	Fe^{3+}, Fe^{2+}	55.85	100	0.01
Manganese	Mn	Mn^{2+}	54.94	50	0.005
Boron	B	BO_3^{2-}, $B_4O_7^{2-}$	10.82	20	0.002
Zinc	Zn	Zn^{2+}	65.38	20	0.002
Copper	Cu	Cu^{2+}, Cu^+	63.54	6	0.0006
Molybdenum	Mo	MoO_4^{2-}	95.96	0.1	0.00001

Source: Modified from Stout P.R., *Proc. of the 9th Ann. Calif. Fert. Conf.* 1961. pp. 21–23.

the urease enzyme activity. Silicone is needed for support. It adds strength to tissues, giving resistance to fungal infection, especially in cucumbers, where it is now common practice to include 100 ppm in the nutrient solution through the use of potassium silicate.

Normally, commercial growers use fertilizer salts containing many of the above elements in trace amounts.

The roles of the essential elements are summarized in Table 2.2. All of them play some role in the manufacture and breakdown of various metabolites required for plant growth. Many are found in enzymes and coenzymes that regulate the rate of biochemical reactions. Others are important in energy-carrying compounds and food storage.

2.3 PLANT MINERAL AND WATER UPTAKE

Plants normally obtain their water and mineral needs from the soil. In a soilless medium, the plants must still be provided with water and minerals. Therefore, in order to understand plant relations in a hydroponic system, we must understand the soil–plant relations under which they normally grow.

2.3.1 The Soil

Soil provides four needs of a plant: (1) supply of water; (2) supply of essential nutrients; (3) supply of oxygen; and (4) support for the plant root system. Mineral soils consist of four major components: mineral elements, organic matter, water, and air. For example, a volume composition

TABLE 2.2
Functions of the Essential Elements within the Plant

1. Nitrogen
Part of a large number of necessary organic compounds, including amino acids, proteins, coenzymes, nucleic acids, and chlorophyll

2. Phosphorus
Part of many important organic compounds, including sugar phosphates, ATP, nucleic acids, phospholipids, and certain co-enzymes

3. Potassium
Acts as a coenzyme or activator for many enzymes (e.g., pyruvate kinase). Protein synthesis requires high potassium levels. Potassium does not form a stable structural part of any molecules inside plant cells

4. Sulfur
Incorporated into several organic compounds including amino acids and proteins. Coenzyme A and the vitamins thiamine and biotin contain sulfur

5. Magnesium
An essential part of the chlorophyll molecule and required for activation of many enzymes, including those involved in ATP bond breakage. Essential to maintain ribosome structure

6. Calcium
Often precipitates as crystals of calcium oxalate in vacuoles. Found in cell walls as calcium pectate, which cements together primary walls of adjacent cells. Required to maintain membrane integrity and is part of the enzyme alpha-amylase. Sometimes interferes with the ability of magnesium to activate enzymes

7. Iron
Required for chlorophyll synthesis and is an essential part of the cytochromes, which act as electron carriers in photosynthesis and respiration. Is an essential part of ferredoxin and possibly nitrate reductase. Activates certain other enzymes

8. Chlorine
Required for photosynthesis, where it acts as an enzyme activator during the production of oxygen from water. Additional functions are suggested by effects of deficiency on roots

9. Manganese
Activates one or more enzymes in fatty acid synthesis, the enzymes responsible for DNA and RNA formation, and the enzyme isocitrate dehydrogenase in the Krebs cycle. Participates directly in the photosynthetic production of O_2 from H_2O and may be involved in chlorophyll formation

10. Boron
Role in plants not well understood. May be required for carbohydrate transport in the phloem

11. Zinc
Required for the formation of the hormone indoleacetic acid. Activates the enzymes alcohol dehydrogenase, lactic acid dehydrogenase, glutamic acid dehydrogenase, and carboxypeptidase

12. Copper
Acts as an electron carrier and as part of certain enzymes. Part of plastocyanin, which is involved in photosynthesis, and also of polyphenol oxidase and possible nitrate reductase. May be involved in N_2 fixation

13. Molybdenum
Acts as an electron carrier in the conversion of nitrate to ammonium and is also essential for N_2 fixation

14. Carbon
Constituent of all organic compounds found in plants

15. Hydrogen
Constituent of all organic compounds of which carbon is a constituent. Important in cation exchange in plant-soil relations

16. Oxygen
Constituent of many organic compounds in plants. Only a few organic compounds, such as carotene, do not contain oxygen. Also involved in anion exchange between roots and the external medium. It is a terminal acceptor of H^+ in aerobic respiration

of a representative silt loam soil in optimum condition for plant growth may consist of 25% water space, 25% air space, 45% mineral matter, and 5% organic matter. The mineral (inorganic) matter is made up of small rock fragments and minerals of various kinds. The organic matter represents an accumulation of partially decayed plant and animal residues. The soil organic matter consists of two general groups: (1) original tissue and its partially decomposed equivalents; and (2) humus. The original tissue includes undecomposed plant and animal matter, which is subject to attack by soil organisms, both plant and animal, which use it as a source of energy and as tissue-building material. Humus is the more resistant product of decomposition, both synthesized by the microorganism and modified from the original plant tissue.

Soil water is held within the soil pores and together with its dissolved salts makes up the soil solution, which is important as a medium for supplying nutrients to growing plants. Soil air located in the soil pores has a higher carbon dioxide and lower oxygen content than that found in the atmosphere. Soil air is important in providing oxygen and carbon dioxide to all soil organisms and plant roots.

The ability of the soil to provide adequate nutrition to the plant depends on four factors: (1) the amounts of the various essential elements present in the soil; (2) their forms of combination; (3) the processes by which these elements become available to plants; and (4) the soil solution and its *p*H. The amounts of the various elements present in the soil depend on the nature of the soil and on its organic matter content, since it is a source of several nutrient elements. Soil nutrients exist both as complex, insoluble compounds and as simple forms usually soluble in soil water and readily available to plants. The complex forms must be broken down through decomposition to the simpler and more available forms in order to benefit the plant. These available forms are summarized in Table 2.1. The reaction of the soil solution (*p*H) determines the availability of the various elements to the plant. The *p*H value is a measure of acidity or alkalinity. A soil is acid if the *p*H is less than 7, neutral if the *p*H is at 7 and alkaline if the *p*H is above 7. Since *p*H is a logarithmic function, a one-unit change in *p*H is a 10-fold change in H^+ concentration. Therefore, any unit change in *p*H can have a large effect on the ion availability to plants. Most plants prefer a *p*H level between 6.0 and 7.0 for optimum nutrient uptake. The effect of *p*H on availability of essential elements is shown in Figure 2.1.

Iron, manganese, and zinc become less available as the *p*H is raised from 6.5 to 7.5 or 8.0. Molybdenum and phosphorus availability, on the other hand, is affected in the opposite way, being greater at the higher *p*H levels. At very high *p*H, bicarbonate ion (HCO_3^-) may be present in sufficient quantities to interfere with the normal uptake of other ions and thus is detrimental to optimum growth.

When inorganic salts are placed in a dilute solution, they dissociate into electrically charged units called *ions*. These ions are available to the plant from the surface of soil colloids and from salts in the soil solution. Positively charged ions (*cations*), such as potassium (K^+) and calcium (Ca^{2+}), are mostly absorbed by the soil colloids, whereas negatively charged ions (*anions*), such as chloride (Cl^-) and sulfate (SO_4^{2-}) are found in the soil solution.

2.3.2 Soil and Plant Interrelations

Plant rootlets and root hairs are in very intimate contact with soil colloidal surfaces. Nutrient uptake by the plants' roots takes place at the surface of the soil colloids and through the soil solution proper, as shown in Figure 2.2. Ions are interchanged between the soil colloids and soil solution. Movement of ions takes place between plant root surfaces and soil colloids and between plant root surfaces and soil solution in both directions. A good review of soil properties is presented by Buckman and Brady (1984) and that of plant and soil interrelations by Kramer (1969).

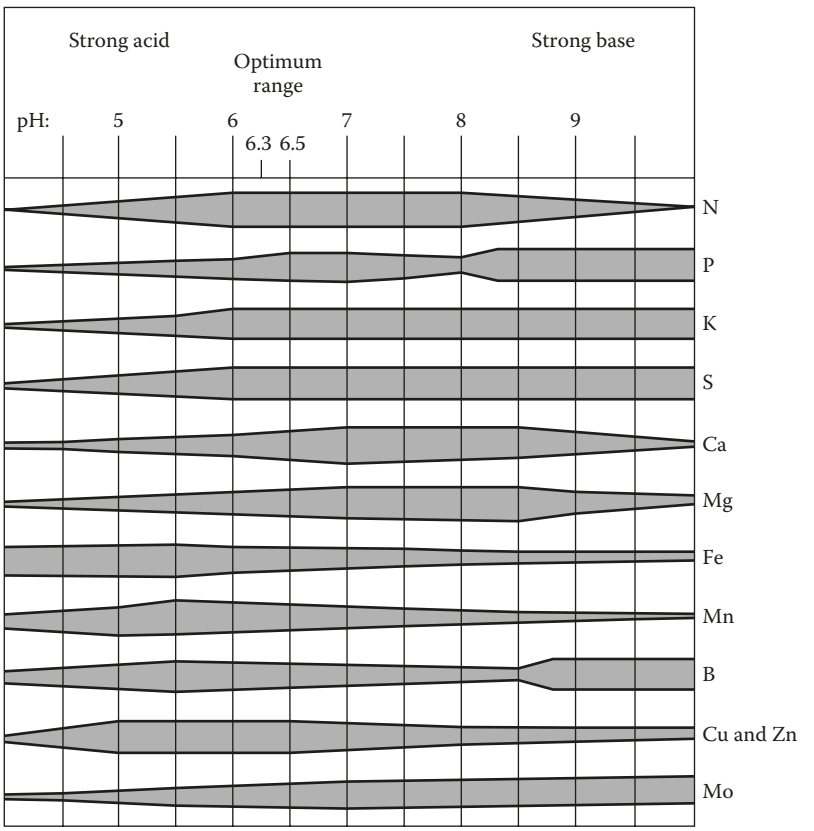

FIGURE 2.1 The effect of soil pH on the availability of plant nutrient uptake. (Modified from Sprague, H.B., *Hunger Signs in Crops.* 1964, p. 18. Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

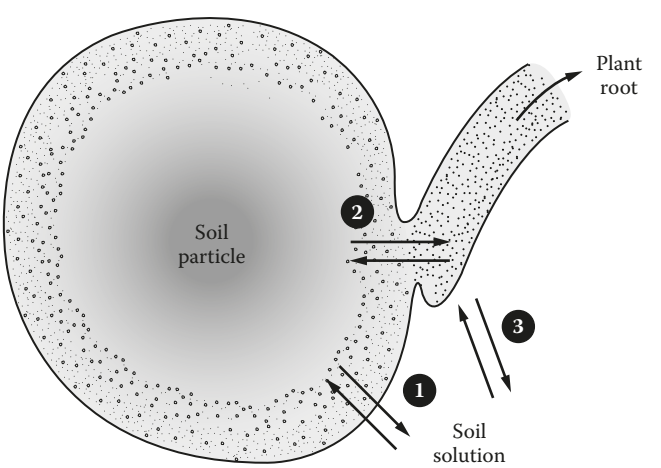

FIGURE 2.2 The movement of nutrients between plant roots and soil particles. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

Notes:
1 = Interchange between soil particles and the soil solution.
2 = Movement of the ions from the soil colloids (particles) to the plant root surface and vice versa.
3 = Interchange between the soil solution and the absorbing surface of plant root systems.

2.3.3 Cation Exchange

The soil solution is the most important source of nutrients for absorption by plant roots. Since it is very dilute, as plants deplete the nutrients from the soil solution, they must be replenished from the soil particles. The solid phase of the soil releases mineral elements into the soil solution partly by solubilization of soil minerals and organic matter, partly by solution of soluble salts, and partly by cation exchange. The negatively charged clay particles and solid organic matter of the soil hold cations, such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), and hydrogen ions (H^{+}). Anions, such as nitrate (NO_3^{-}), phosphate (HPO_4^{2-}), sulfate (SO_4^{2-}), chloride (Cl^{-}), and others are found almost exclusively in the soil solution. Cations are also found in the soil solution, and their ability to exchange freely with cations absorbed on the soil colloids enables cation exchange to take place.

2.3.4 Soil versus Hydroponics

There is no physiological difference between plants grown hydroponically and those grown in soil. In soil, both the organic and inorganic components must be decomposed into inorganic elements, such as calcium, magnesium, nitrogen, potassium, phosphorus, iron, and others before the are available to the plant (Figure 2.3). These elements adhere to the soil particles and are exchanged into the

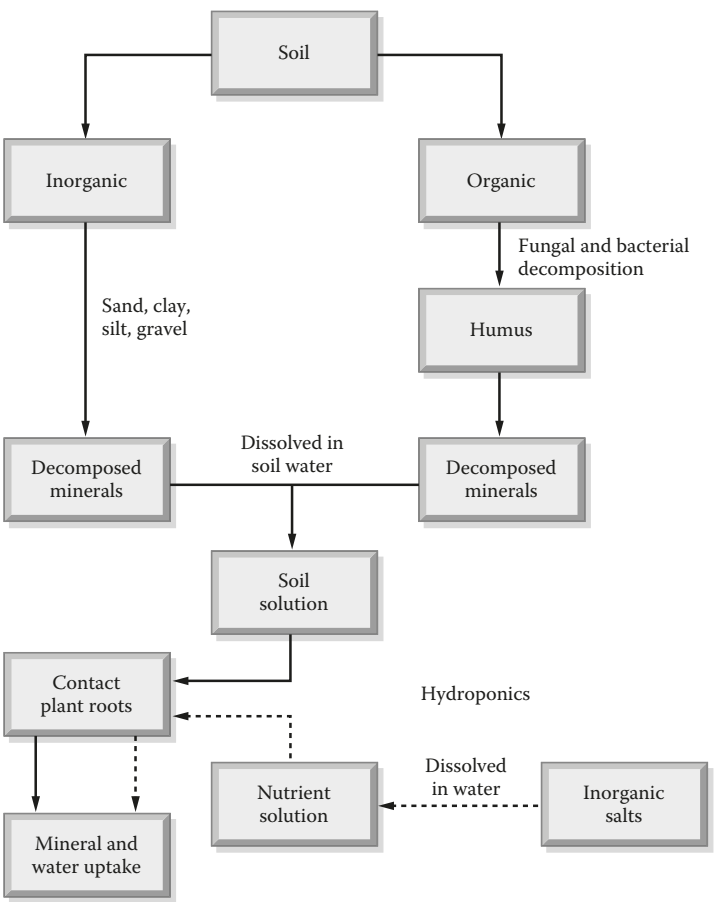

FIGURE 2.3 Origin of essential elements in soil and hydroponics. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

soil solution where they are absorbed by the plants. In hydroponics, the plant roots are moistened with a nutrient solution containing the elements. The subsequent processes of mineral uptake by the plant are the same, as detailed in Sections 2.3.5 and 2.3.6.

2.3.5 Transfer of Water and Solutes from Soil (or Nutrient Solution) to Root

The use of the term "organic" in the marketing of vegetables is really a misnomer as all plants are organic and use the same essential mineral elements. The term "organic" refers to the non-use of synthetic pesticides and therefore should be called "free of synthetic pesticides." The question of organic versus inorganic gardening can be clarified by a discussion of mineral uptake by the plant.

In 1932, E. Munch of Germany introduced the apoplast-symplast concept to describe water and mineral uptake by plants. He suggested that water and mineral ions move into the plant root via the interconnecting cell walls and intercellular spaces, including the xylem elements, which he called the *apoplast*, or via the system of interconnected protoplasm (excluding the vacuoles), which he termed the *symplast*. However, whatever the movement may be, its uptake is regulated by the endodermal layer of cells around the stele, which constitutes a barrier to free movement of water and solutes through the cell walls. There is a waxy strip, the Casparian strip, around each endodermal cell, which isolates the inner portion of the root (stele) from the outer epidermal and cortex regions in which water and mineral movement is relatively free.

If the root is in contact with a soil (nutrient) solution, ions will diffuse into the root via the apoplast across the epidermis, through the cortex, and up to the endodermal layer. Some ions will pass from the apoplast into the symplast by an active respiration-requiring process. Since the symplast is continuous across the endodermal layer, ions can move freely into the pericycle and other living cells within the stele (Figure 2.4).

2.3.6 Movement of Water and Minerals across Membranes

If a substance is moving across a cell membrane, the number of particles moving per unit of time through a given area of the membrane is termed the *flux*. The flux is equal to the permeability of

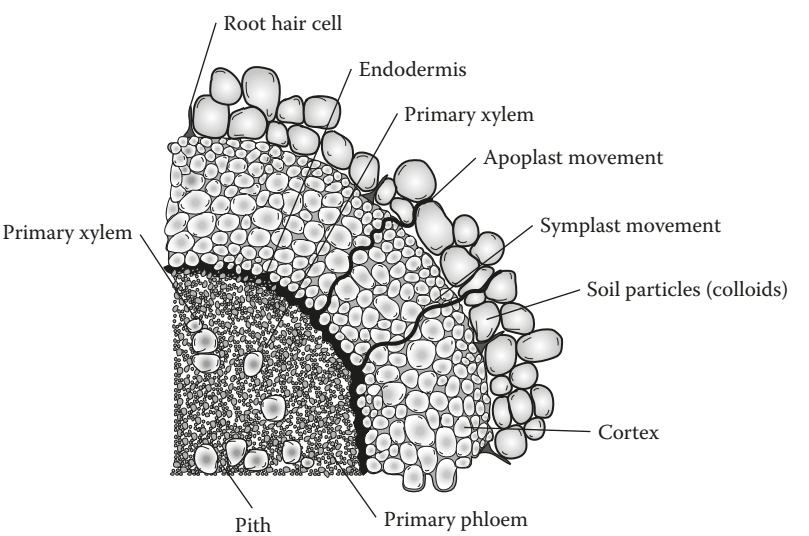

FIGURE 2.4 A cross section of a root with movement of water and nutrients. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

the membrane multiplied by the driving force causing diffusion. The driving force is due to the difference in concentration (the chemical potential) of that ion on the two sides of the membrane. If the chemical potential of the solute is higher outside the membrane than inside, the transport inward is passive. That is, energy is not expended by the plant to take up the ion. If, however, a cell accumulates ions against a chemical potential gradient, it must provide energy sufficient to overcome the difference in chemical potential. Transport against a gradient is active since the cells must actively metabolize in order to carry out the solute uptake.

When ions are transported across membranes, the driving force is composed of both a chemical and electrical potential difference. That is, an electrochemical potential gradient exists across the membrane. The electrical potential difference arises from cations diffusing across more rapidly than the corresponding anions of a salt. Thus, the inside will become positive with respect to the outside. Whether the transport of an ion is active or passive depends on the contribution of both the electrical potential difference and the chemical potential difference. Sometimes, these two factors will act in the same direction, while in other cases, they act oppositely. For example, a cation might have a higher concentration inside the cell and yet be transported inward passively with no energy expenditure on the part of the cell if the electrical potential is sufficiently negative. On the other hand, anion absorption against both a chemical potential gradient and a negative electrical potential would always be an active process.

There are a number of theories proposed to explain how respiration and active absorption are coupled, but most of them employ the mechanism of a carrier. For example, when an ion contacts the outside of a membrane of a cell, neutralization may occur as the ion is attached to some molecular entity that is a part of the membrane. The ion attached to this carrier might then diffuse readily across the membrane, being released on the opposite side. The attachment may require the expenditure of metabolic energy and can occur on only one side of the membrane, while release can occur only on the other side of the membrane. The ions separate and move into the cell and the carrier becomes available to move more ions (Figure 2.5). Selectivity in ion accumulation could be controlled by differences in ability of carriers to form specific combinations with various ions. For example, potassium absorption is inhibited competitively by rubidium, indicating that the two ions use the same carrier or the same site on the carrier.

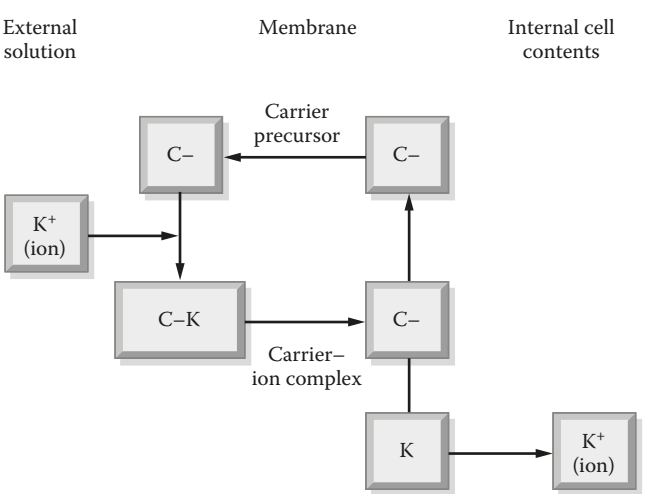

FIGURE 2.5 Movement of ions across cell membranes by a carrier. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

As previously indicated, the foregoing explanation of mineral uptake by plant roots has been presented in an effort to clarify the question of organic versus inorganic gardening. The existence of specific relationships between ions and their carriers, which enables their transport across cell membranes to enter the cell, demonstrates that mineral uptake functions in the same manner whether the source of such minerals is from organic matter or from fertilizers. Large organic compounds making up soil humus are not absorbed by the plant, but must first undergo decomposition into the basic inorganic elements. They can be accumulated by their contact with plant cell membranes only in their ionic form. Thus, organic gardening cannot provide to the plant any compound that cannot exist in a hydroponic system. The function of organic matter in soil is to supply inorganic elements for the plant and at the same time maintain the structure of the soil in optimum condition so that these minerals will be available to the plant. Thus, the indiscriminate application of large amounts of fertilizers to soil without the addition of organic matter results in a breakdown of the soil structure and subsequently makes the abundant supply of minerals unavailable to the plant. This is not the fault of the fertilizer but its misuse in soil management.

2.4 THE UPWARD MOVEMENT OF WATER AND NUTRIENTS

Water, with its dissolved minerals, moves primarily upward in the plant through xylem tissue. The xylem, composed of several cell types, forms a conduit system within the plant. This vascular tissue is commonly termed *vein.* Veins are actually composed of xylem and phloem tissue. The phloem tissue is the main conduit of manufactured food. The actual phloem translocation of photosynthates is still not fully understood. In general, water and minerals move upward in the xylem to the sites of photosynthesis, and photosynthates move from this source of manufacture to other parts of the plant.

The ascent of sap within a plant was suggested by Dixon and Renner in their cohesion hypothesis. They claimed that the force sucking up water and nutrients from the soil into the plant root comes from water evaporation from cell walls in the leaves. The binding force is in the inherent tensile strength of water, a property arising from cohesion of the water molecules (the forces of attraction between water molecules).

This cohesion of water in the xylem is due to the capillary dimensions of the xylem elements. The water uptake from the soil comes from the negative water potential, which is transferred down the plant to the root cells and soil by the upward driving force of evaporation.

The leaves of plants have a waxy cuticle cover on the outside surface to prevent excessive water loss by evaporation (Figure 2.6). Small pores (*stomates*) in the epidermis, particularly numerous in the lower epidermis, regulate the passage of carbon dioxide and oxygen in and out of the leaf. Water vapor also moves through these openings. Therefore, water loss is regulated largely by the stomates. Water moves from the xylem vessels in the veins to the leaf mesophyll cells, evaporates, and diffuses through the stomates into the atmosphere. This water loss in evapotranspiration must be replaced by water entering the plant roots, or water stress will result, which if continued, will lead to death of the plant. In the process of water uptake, minerals are transported to chlorophyll-containing cells (palisade parenchyma, spongy mesophyll, and bundle sheath cells, if present), where they are used in the manufacture of foods through the process of photosynthesis.

2.5 PLANT NUTRITION

As mentioned in Chapter 1, hydroponics developed through studies of plant constituents, which led to the discovery of plant essential elements. Plant nutrition is therefore the basis of hydroponics. Anyone intending to employ hydroponic techniques must have a thorough knowledge of plant nutrition. The management of plant nutrition through management of the nutrient solution is the key to successful hydroponic growing.

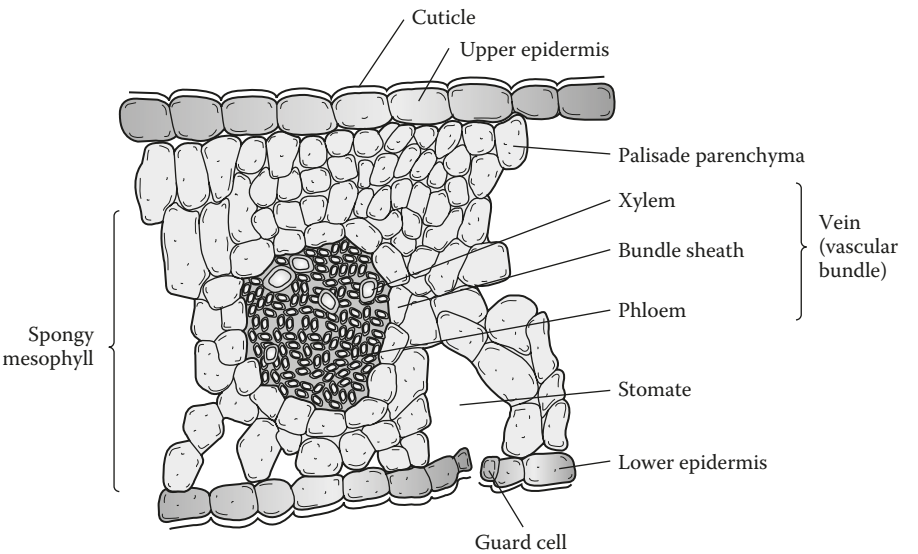

FIGURE 2.6 Cross section of a typical broad-leaved plant leaf. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

The absorption and transport of plant nutrients within the plant has already been discussed. The next question is how to maintain the plant in an optimum nutrient status. Hydroponics enables us to do this, but it also presents the risk of error, which could result in rapid starvation or other adverse effects on the plant. A diagnostic program to determine the nutritional level of the plant at any time is extremely important to avoid nutritional stresses that limit plant growth.

The ideal method of diagnosing the nutritional status of plants is to take tissue analyses of plant leaves periodically and in conjunction with these tests, nutrient solution analyses. The level of each essential element in the plant tissue and nutrient solution must be determined and correlated so that, if needed, adjustments can be made in the nutrient solution to avoid potential nutritional problems. Of course, such a program is costly in terms of time and labor and is not always economically feasible. These analyses can be done by commercial laboratories (Appendix 2), but sometimes results are slow and crop damage may occur before recommendations are received.

The alternative to such laboratory analyses is visual diagnosis of nutrient stress symptoms expressed by the plant. However, it must be emphasized that once the plant shows symptoms it has already undergone severe nutritional stress and will take some time to regain its health after remedial steps have been taken. Therefore, it is important to correctly identify the nutrient problem immediately in order to prevent the plant from losing vigor.

For further study of plant physiology and nutrition, refer to Salisbury and Ross (1992), Epstein and Bloom (2005), and Gauch (1972).

2.5.1 Nutritional Disorders

A nutritional disorder is a malfunction in the physiology of a plant, resulting in abnormal growth caused by either a deficiency or excess of a mineral element(s). The disorder is expressed by the plant externally and/or internally in the form of symptoms. Diagnosis of a nutritional disorder involves accurate description and identification of the disorder. A deficiency or excess of each essential element causes distinct plant symptoms, which can be used to identify the disorder.

Elements are grouped basically into those that are mobile and those that are immobile, with some having gradations of mobility. Mobile elements are those that can be retranslocated. They will move from their original site of deposition (older leaves) to the actively growing region of the plant (younger leaves) when a deficiency occurs.

As a result, the first symptoms will appear on the older leaves on the lower portion of the plant. The mobile elements are magnesium, phosphorus, potassium, zinc, and nitrogen. When a shortage of the immobile elements occurs; they are not retranslocated to the growing region of the plant, but remain in the older leaves where they were originally deposited. Deficiency symptoms, therefore, first appear on the upper young leaves of the plant. The immobile elements include calcium, iron, sulfur, boron, copper, and manganese.

It is important to detect nutritional disorders early, since as they increase in severity the symptoms spread rapidly over the entire plant, resulting in the death of much of the plant tissue. Then symptom characteristics, such as chlorosis (yellowing) and necrosis (browning) of the plant tissue, become very general. In addition, disorders of one element often upset the plant's ability to accumulate other elements, and shortly, two or more essential elements are simultaneously deficient or in excess. This is particularly true of nutrient deficiencies. When two or more elements are deficient simultaneously, the composite picture or syndrome expressed by the symptoms may resemble no given deficiency. Under such conditions, it is generally impossible to determine visually which elements are responsible for the symptoms.

Often a deficiency of one element leads to antagonism toward the uptake of another element. For instance, boron deficiency can also cause calcium deficiency. Calcium deficiency may lead to potassium deficiency and vice versa. The need for accurate and fast identification of a symptom expression cannot be overemphasized. It is often beneficial to grow an indicator plant along with the regular crop. The susceptibility of different plant species to various nutritional disorders varies greatly. For example, if a crop of tomatoes is being grown, plant a few cucumbers, lettuce, or even a weed or two if it is known to be very sensitive to nutritional disorders. Cucumbers are very sensitive to boron and calcium deficiency. If such a deficiency occurs, the cucumbers will express symptoms from several days to a week before they appear on the tomatoes. Such early warning enables the grower to adjust the nutrient solution to prevent a deficiency in the tomato crop. In addition, weaker plants of the same species will show symptoms before the more vigorous ones. Every possible tactic must be employed to avoid a nutritional disorder in the main crop, since once symptoms are expressed in the crop, some reduction in yield is inevitable.

Once a nutritional disorder has been identified, steps to remedy it can be taken. In a hydroponic system, the first step is to change the nutrient solution. This should be done as soon as a nutritional disorder is suspected, even before it is identified. If the disorder has been diagnosed as a deficiency, a foliar spray can be applied for a rapid response. However, care must be taken not to use a concentration high enough to burn the plants. It is best to try the recommended foliar spray on a few plants and then observe the results for several days before treating the whole crop. The nutrient formulation probably will have to be adjusted (Chapter 3) to overcome the disorder. If a nutrient deficiency is present, the level of deficient nutrient should be increased to an above-normal level (up to 25–30%). As the plants come out of the deficiency, the increase in the identified nutrient could be lowered to about 10–15% above the level at which the deficiency occurred. Depending on the severity of disorder, weather conditions, and the element itself, the plant may take 7–10 d before response toward the control measure is evident.

If toxicity has occurred, the soilless medium will have to be flushed with water alone to reduce residual levels in the medium. Flushing may have to be done over a period of a week or so depending again on the severity of the disorder. However, nutrient deficiencies are far more common than toxicities in hydroponics. For this reason, nutrient deficiencies are emphasized in the following discussion on symptomatology.

2.5.2 Symptomatology

One of the first steps in identifying a nutritional disorder is to describe the symptoms in distinct, accurate terms. Table 2.3 summarizes terms commonly used in symptomatology. When observing a disorder, determine what plant part or organ is affected. Does it occur on the lower older leaves or the upper younger leaves? Are the symptoms on the stem, fruit, flowers, and/or growing point of the plant? What is the appearance of the whole plant? Is it dwarfed, deformed, or branched excessively? What is the nature of the ailment? Is the tissue chlorotic (yellow), necrotic (brown), or deformed? Then, describe the color pattern and location of this chlorosis, necrosis, or deformation using the terms given in Table 2.3.

After the symptoms have been observed closely and described, it should be determined whether the disorder may be caused by something other than a nutritional imbalance.

Other possible disorders to check include insect damage, parasitic diseases, pesticide damage, pollution damage, water stress, light and temperature injury. Pesticide damage may cause burning if greater than recommended dosages are used on the plants. Also, the use of herbicides such as 2,4-D near a greenhouse may cause deformation of plant leaves closely resembling the symptoms of tobacco mosaic virus (TMV). Pollution damage may cause burning or bleaching of leaf tissue or a stippled effect (pinpoint-sized chlorotic spots) on leaves. Water stress, either lack or excess of water, will cause wilting (loss of turgidity) of leaves. Excessive sunlight or temperature may burn and dry leaf tissue, particularly on the margins.

TABLE 2.3
Terminology used in the Description of Symptoms on Plants

Term	Description
Localized	Symptoms limited to one area of plant or leaf
Generalized	Symptoms not limited to one area but spread generally over entire plant or leaf
Drying (firing)	Necrosis – scorched, dry, papery appearance
Marginal	Chlorosis or necrosis – on margins of leaves initially; usually spreads inward as symptom progresses
Interveinal chlorosis	Chlorosis (yellowing) between veins of leaves only
Mottling	Irregular spotted surface – blotchy pattern of indistinct light and dark areas; often associated with virus diseases
Spots	Discolored area with distinct boundaries adjacent to normal tissue
Color of leaf undersides	Often a particular coloration occurs mostly or entirely on the lower surface of the leaves, for example, phosphorus deficiency – purple coloration of leaf undersides
Cupping	Leaf margins or tips may cup or bend upward or downward, for example, copper deficiency – margins of leaves curl into a tube; potassium deficiency – margins of leaves curl inward.
Checkered (reticulate)	Pattern of small veins of leaves remaining green while interveinal tissue yellows – manganese deficiency
Brittle tissue	Leaves, petioles, stems may lack flexibility, break off easily when touched – calcium or boron deficiency
Soft tissue	Leaves very soft, easily damaged – nitrogen excess
Dieback	Leaves or growing point dies rapidly and dries out – boron or calcium deficiencies
Stunting	Plant shorter than normal
Spindly	Growth of stem and leaf petioles very thin and succulent

TABLE 2.4
A Key to Mineral Deficiency Symptoms

Symptoms	Deficient Element
A. Older or lower leaves affected.	
B. General chlorosis and/or drying of lower leaves, retarded growth.	
C. Chlorosis progresses from light green to yellow, from older leaves up to new growth. Growth is restricted, spindly, loss of older leaves……	Nitrogen
CC. Leaves remain dark green, growth restricted, and distinctive purple coloration of undersides of leaves. Lower leaves dry. Root growth is restricted. Fruit-set delayed…….	Phosphorous
BB. Localized mottling or chlorosis with or without dead spots, no drying of lower leaves.	
C. Interveinal chlorosis, mottled effect with green veins. Margins curl upward, necrotic spots, stalks slender……	Magnesium
CC. Mottled or chlorotic leaves with spots of dead tissue.	
D. Small dead spots at tips and between veins. Margins cup downward with brown spots. Growth is restricted, slender stalks. Roots poorly developed…….	Potassium
DD. Spots generalized, rapidly enlarging to include veins, leaves thick, stalks with shortened internodes. Young leaves small, interveinal chlorosis, mottled, curl downward……	Zinc
E. Mottling of older leaves with veins remaining light green. Leaf margins become necrotic, may curl upward, necrotic spots of leaf tips and margins. Symptoms spread to younger leaves as deficiency progresses……	Molybdenum
AA. Symptoms appear first in young leaves – terminal growth.	
B. Growing tip distorted, young leaves at tips chlorotic with necrotic spots expanding to browning of leaf margins and dieback.	
C. Brittle tissues not present in growing tips, young leaves chlorotic, old leaves remain green, stems thick and woody, growing tip necrotic followed by dieback, blossom-end-rot of fruit (especially tomatoes)……	Calcium
CC. Growing tip – leaves and petioles – light green to yellow, brittle tissue, often deformed or curled. Rosetting of terminal growth due to shortening of internodes. Terminal bud dies, new growth may form at lower leaf axils, but these suckers (especially tomatoes) show similar symptoms of chlorosis, necrosis, browning and brittleness. Internal browning, open locules, blotchy ripening of tomato fruit……..…	Boron
BB. Growing tip alive, not distorted, wilting or chlorosis with or without dead spots, veins light or dark green.	
C. Young leaves wilt, chlorosis, necrosis, retarded growth, lodging of growing tip……...	Copper
CC. Young leaves not wilted, chlorosis with or without necrosis and dead spots.	
D. Interveinal chlorosis, veins remain green to give checkered pattern. Chlorotic areas become brown to later form necrotic spots of dead tis sue……..……..……..……	Manganese
DD. Interveinal dead spots not present, chlorosis of tissue may or may not involve veins.	
E. Leaves uniformly light green becoming yellow, veins not green, poor, spindly growth, hard and woody stems……	Sulfur
EE. Tissue between veins yellows, veins green, eventually veins become chlorotic. Yellow interveinal tissue becomes white, but no necrosis. Stems slender, short. Flowers abort and fall off, tomato flower clusters are small, thin stemmed ……	Iron

Once the above factors have been checked and eliminated as potential causes, a nutritional disorder would be suspected. Generally, in hydroponics, nutritional disorders will appear on all plants at the same time and progress to others. The next step is to identify the nutrient disorder(s) by the use of a "key" (Table 2.4). Deficiency and toxicity symptoms for all the essential elements are given in Table 2.5. These two tables describe symptoms for most plants. Since different plant species will express various symptoms to a lesser or greater degree than others, Table 2.6 is included on specific symptoms and remedies for tomatoes, cucumbers, peppers, and lettuce.

TABLE 2.5
Deficiency and Toxicity Symptoms for Essential Elements

1. Nitrogen

Deficiency Symptoms: Growth is restricted and plants are generally yellow (chlorotic) from lack of chlorophyll, especially older leaves. Younger leaves remain green longer. Stems, petioles, and lower leaf surfaces of corn and tomato can turn purple

Toxicity Symptoms: Plants usually dark green in color with abundant foliage but usually with a restricted root system. Potatoes form only small tubers, and flowering and seed production can be retarded

2. Phosphorus

Deficiency Symptoms: Plants are stunted and often a dark green color. Anthocyanin pigments may accumulate. Deficiency symptoms occur first in more mature leaves. Plant maturity often delayed

Toxicity Symptoms: No primary symptoms yet noted. Sometimes copper and zinc deficiency occurs in the presence of excess phosphorus

3. Potassium

Deficiency Symptoms: Symptoms first visible on older leaves. In dicots, these leaves are initially chlorotic but soon scattered dark necrotic lesions (dead areas) develop. In many monocots, the tips and margins of the leaves die first. Potassium-deficient corn develops weak stalks and is easily lodged

Toxicity Symptoms: Usually not excessively absorbed by plants. Oranges develop coarse fruit at high potassium levels. Excess potassium may lead to magnesium deficiency and possible manganese, zinc or iron deficiency

4. Sulfur

Deficiency Symptoms: Not often encountered. Generally yellowing of leaves, usually first visible in younger leaves

Toxicity Symptoms: Reduction in growth and leaf size. Leaf symptoms often absent or poorly defined. Sometimes interveinal yellowing or leaf burning

5. Magnesium

Deficiency Symptoms: Interveinal chlorosis, which first develops on the older leaves. The chlorosis may start at leaf margins or tip and progress inward interveinally

Toxicity Symptoms: Very little information available on visual symptoms

6. Calcium

Deficiency Symptoms: Bud development is inhibited, and root tips often die. Young leaves are affected before old leaves and become distorted and small with irregular margins and spotted or necrotic areas

Toxicity Symptoms: No consistent visible symptoms. Usually associated with excess carbonate

7. Iron

Deficiency Symptoms: Pronounced interveinal chlorosis similar to that caused by magnesium deficiency but on the younger leaves

Toxicity Symptoms: Not often evident in natural conditions. Has been observed after the application of sprays where it appears as necrotic spots

TABLE 2.5 (Continued)
Deficiency and Toxicity Symptoms for Essential Elements

8. Chlorine

Deficiency Symptoms: Wilted leaves which then become chlorotic and necrotic, eventually attaining a bronze color. Roots become stunted and thickened near tips

Toxicity Symptoms: Burning or firing of leaf tip or margins. Bronzing, yellowing, and leaf abscission and sometimes chlorosis. Reduced leaf size and lower growth rate

9. Manganese

Deficiency Symptoms: Initial symptoms are often interveinal chlorosis on younger or older leaves depending on species. Necrotic lesions and leaf shedding can develop later. Disorganization of chloroplast lamellae

Toxicity Symptoms: Sometimes chlorosis, uneven chlorophyll distribution, and iron deficiency (pineapple). Reduction in growth

10. Boron

Deficiency Symptoms: Symptoms vary with species. Stem and root apical meristems often die. Root tips often become swollen and discolored. Internal tissues sometimes disintegrate (or discolor) (e.g. "heart rot" of beets). Leaves show various symptoms including thickening, brittleness, curling, wilting, and chlorotic spotting

Toxicity Symptoms: Yellowing of leaf tip followed by progressive necrosis of the leaf beginning at tip or margins and proceeding toward midrib

11. Zinc

Deficiency Symptoms: Reduction in internode length and leaf size. Leaf margins are often distorted or puckered. Sometimes interveinal chlorosis

Toxicity Symptoms: Excess zinc commonly produces iron chlorosis in plants

12. Copper

Deficiency Symptoms: Natural deficiency is rare. Young leaves often become dark green and twisted or misshapen, often with necrotic spots

Toxicity Symptoms: Reduced growth followed by symptoms of iron chlorosis, stunting, reduced branching, thickening, and abnormal darkening of rootlets

13. Molybdenum

Deficiency Symptoms: Often interveinal chlorosis developing first on older or midstem leaves, then progressing to the youngest. Sometimes leaf marginal scorching or cupping

Toxicity Symptoms: Rarely observed. Tomato leaves turn golden yellow

For further study of nutritional disorders, refer to Roorda van Eysinga and Smilde (1980). Sprague (1964) published a review of symptoms in plants due to mineral deficiencies and toxicities.

2.5.3 Use of a Key

The key presented here is a dichotomous table. A decision must be made at each alternative route, and finally a single explanation is given at the end. The key to nutritional disorders is based on symptoms observed on the plant, hence the importance of accurate symptom description. The key (Table 2.4) is for use in determining mineral deficiencies only, not toxicities.

The first decision concerns effects on older leaves (A) versus effects on upper younger leaves (AA). Once this choice is made, a series of choices follows. The next step is (B) versus (BB) under the previous choice of (A) or (AA). Then, (C) versus (CC), (D) versus (DD), and so on. For example, use the key to find the following symptoms: the young (upper) leaves of a plant are chlorotic, the veins green, and no dead spots are visible. The terminal bud is alive and not wilted. The older (lower) leaves show no symptoms. The terminal growing area is somewhat spindly, and there is

TABLE 2.6
Summary of Mineral Deficiencies in Tomatoes, Cucumbers, Peppers, Lettuce and Remedies

Mobile elements (first symptoms on older leaves)

1. Nitrogen

Tomatoes
spindly plant
lower leaves – yellowish green
severe cases – entire plant pale green
major veins – purple color
small fruit

Cucumbers
stunted growth
lower leaves – yellowish green
severe cases – entire plant pale green
younger leaves stop growing
fruit – short, thick, light green, spiny

Peppers
slow growth
few flowers, poor fruit set
thin fruit receptacle, small ovary
no fruit or deformed fruit

Lettuce
restricted growth of plant and roots
yellow-green leaves
small leaves

Remedies:
1. Use a foliar spray of 0.25%–0.5% solution of urea (not lettuce or leafy greens)
2. Add calcium nitrate or potassium nitrate to nutrient solution

2. Phosphorus

Tomatoes
shoot growth restricted, thin stem
severe cases – leaves small, stiff, curved downward
leaf upper sides – bluish green
leaf undersides – including veins – purple
older leaves – yellow with scattered purple dry spots premature leaf drop

Cucumbers
stunted
severe cases – young leaves small, stiff, dark green
older leaves and cotyledons – large water-soaked spots including both veins and interveinal areas
affected leaves fade, spots turn brown and desiccate, shrivel – except for petiole

Peppers
growth limited
brittle leaves
few flowers, fruit, if any form may abort
fruit – thin receptacle, few seeds

Lettuce
plants stunted – rosette-like heads
older leaves yellow, die if severe

Remedies:
1. Add Monopotassium phosphate to nutrient solution.

3. Potassium

Tomatoes:
older leaves – leaflets scorched, curled margins, interveinal chlorosis, small dry spots
middle leaves – interveinal chlorosis with small dead spots
plant growth – restricted, leaves remain small
later stages – chlorosis and necrosis spreads over large area of leaves, also up plant, leaflets die back
fruit – blotchy, uneven ripening, greenish areas

Cucumbers
older leaves – discolored yellowish green at margins, later turn brown and dry

plant growth – stunted, short internodes, small leaves
later stages – interveinal and marginal chlorosis extends to center of leaf, also progresses up plant, leaf margins desiccate, extensive necrosis, larger veins remain green

TABLE 2.6 (Continued)
Summary of Mineral Deficiencies in Tomatoes, Cucumbers, Peppers, Lettuce and Remedies

Peppers
older leaves – interveinal yellow spots
fruit set – sparse, if any, setting is small

Lettuce
older leaves – chlorotic spots develop in tips
severe – spots coalesce, become necrotic

Remedies:
1. Foliar spray of 2% potassium sulfate (not lettuce or leafy greens)
2. Add potassium sulfate or if no sodium chloride present in water, can add potassium chloride to nutrient solution

4. Magnesium

Tomatoes
older leaves – marginal chlorosis progressing inwards as interveinal chlorosis, necrotic spots in chlorotic areas
small veins – not green
severe starvation – older leaves die, whole plant turns yellow, fruit production reduced

Cucumbers
older leaves – interveinal chlorosis from leaf margins inward – necrotic spots develop
small veins – not green
severe starvation – symptoms progress from older to younger leaves, entire plant yellows, older leaves shrivel and die

Peppers
older leaves – interveinal yellowing, veins green

Lettuce
older leaves – yellow from edges inward between veins

Remedies:
1. Foliar spray – high-volume spray with 2% magnesium sulfate or low-volume spray with 10% magnesium sulfate (not lettuce or leafy greens)
2. Add magnesium sulfate to nutrient solution

5. Zinc

Tomatoes
older leaves and terminal leaves – smaller than normal
little chlorosis, but irregular shriveled brown spots develop, especially on petiolules (small petioles of leaflets) and on and between veins of leaflets
petioles – curl downward, complete leaves coil up
severe starvation – rapid necrosis, entire foliage withers

Cucumbers
older leaves – interveinal mottling, symptoms progress from older to younger leaves, no necrosis
internodes – at top of plant stop growing, leading to upper leaves closely spaced, giving bushy appearance

Peppers
leaves – small, narrow

Lettuce
leaves – leaf margins dark with necrotic spots, "scorched" look
restricted growth, rosette appearance

Remedies:
1. Foliar spray with 0.1%–0.5% solution of zinc sulfate (not lettuce or leafy greens)
2. Add zinc sulfate to nutrient solution

(*continued*)

TABLE 2.6 (Continued)
Summary of Mineral Deficiencies in Tomatoes, Cucumbers, Peppers, Lettuce and Remedies

Immobile elements (first symptoms on younger leaves)

1. Calcium

Tomatoes
upper leaves – marginal yellowing, undersides turn purple-brown color especially on margins, leaflets remain tiny, deformed, margins curl up
progression to later stages – leaf tips and margins wither, curled petioles die back
growing point dies
older leaves – finally, chlorosis and necrotic spots form
fruit – blossom-end-rot (leather-like decay at blossom ends of fruit)

Cucumbers
upper leaves – white spots near edges and between veins, marginal interveinal chlorosis progresses inward
youngest leaves (growing point region) – remain small, edges deeply incised, curl upwards, later shrivel from edges inwards and growing point dies
plant growth – stunted, short internodes, especially near apex
buds – abort, finally plant dies back from apex
older leaves – curve downwards

Peppers
similar symptoms to tomatoes above
fruit – blossom-end-rot (BER)

Lettuce
leaves – margins necrotic "tip burn"
brittle leaves, crinkled
growth – severely stunted
Note: tip burn can be induced by high relative humidity, and/or high potassium or magnesium levels in nutrient solution restricting calcium uptake

Remedies:
1. Foliar spray in acute cases with 0.75%–1.0% calcium nitrate solution. Can also use 0.4% calcium chloride (not lettuce or leafy greens)
2. Add calcium nitrate to nutrient solution, or calcium chloride if do not want to increase nitrogen level, but be sure there is little, if any, sodium chloride in the nutrient solution if calcium chloride is used
3. For lettuce and leafy greens reduce relative humidity, increase ventilation, reduce potassium and/or magnesium level in nutrient solution so Ca: Mg ratio is 3.5: 1 and Ca: K ratio is 1: 1.3.

2. Sulfur

Tomatoes
upper leaves – stiff, curl downward, eventually large irregular necrotic spots appear, leaves become yellow
stem, veins, petioles – purple
older leaves, leaflets – necrosis at tips and margins, small purple spots between veins

Cucumbers
upper leaves – remain small, bend downwards, pale green to yellow, margins markedly serrate
plant growth – restricted
older leaves – very little yellowing

Peppers
upper leaves – yellow, eventually necrotic spots

Lettuce
leaves – greenish yellow, especially the heart
growth restricted

Remedies:
1. Add any sulfates to the nutrient solution. Potassium sulfate would be safest since the plants require high levels of potassium

Note: Sulfate deficiency rarely occurs since sufficient amounts are added by use of potassium, magnesium and other sulfate salts in the normal nutrient formulation.

TABLE 2.6 (Continued)
Summary of Mineral Deficiencies in Tomatoes, Cucumbers, Peppers, Lettuce and Remedies

3. Iron

Tomatoes
terminal leaves – chlorosis starts at margins and spreads through entire leaf, initially smallest veins remain green, giving reticulate pattern of green veins on yellow leaf tissues; leaf eventually turns completely pale yellow, no necrosis
progression – symptoms start from terminal leaves and work down to older leaves
growth – stunted, spindly, leaves smaller than normal
flowers – abortion

Cucumbers
young leaves – fine pattern of green veins with yellow interveinal tissue, later chlorosis spreads to veins and entire leaves turn lemon-yellow; some necrosis may develop on margins of leaves
progression – from top downward
growth – stunted, spindly
axillary shoots and fruits – also turn lemon-yellow

Peppers
similar to tomatoes above

Lettuce
young leaves – interveinal chlorosis
whole plant turns light green
growth – stunted, eventually stops

Remedies:
1. Foliar spray with 0.02%–0.05% solution of iron chelate (FeEDTA) every 3–4 d (not lettuce or leafy greens)
2. Add iron chelate to nutrient solution

4. Boron

Tomatoes
growing point – shoot growth restricted, leads to withering and dying of growing point
upper leaves – interveinal chlorosis, mottling of leaflets, remain small, curl inward, deformed, smallest leaflets turn brown and die
middle leaves – yellow-orange tints, veins yellow or purple
older leaves – yellowish-green
lateral shoots – growing points die
petioles – very brittle, break off easily, clogged vascular tissue

Cucumbers
apex – growing point plus youngest unexpanded leaves curl up and die
axillary shoots – wither and die
older leaves – cupped upward beginning along margins, stiff, interveinal mottling
shoot tip – stops growing, leads to stunting

Peppers
similar to tomatoes above
growth stunted, thick, short stem
growing point dies
upper leaves misshapen
reduction in flowers, poor fruit set

Lettuce
upper leaves – stiff, rounded with chlorotic mottling at edges and between veins
growing point dies
poor root development
dwarf appearance

Remedies:
1. Apply a foliar spray as soon as detected of 0.1%–0.25% of solution of borax (not lettuce or leafy greens)
2. Add borax to nutrient solution

(*continued*)

TABLE 2.6 (Continued)
Summary of Mineral Deficiencies in Tomatoes, Cucumbers, Peppers, Lettuce and Remedies

5. Copper

Tomatoes
middle and younger leaves – margins curl into a tube toward the midribs, no chlorosis or necrosis, bluish green color, terminal leaves small, stiff and folded up
petioles – bend downward, directing opposite tubular leaflets toward each other
stem-growth stunted
progression – later stages get necrotic spots adjacent to and on midribs and larger veins

Cucumbers
young leaves – remain small
plant growth – restricted, short internodes, bushy plant
older leaves – interveinal chlorosis in blotches
progression – leaves turn dull green to bronze, necrosis, entire leaf

Peppers
leaf margins curl and dry up
leaves and fruit become narrow and rectangular
growth stunted

Lettuce
leaves – narrow and cupped, as chlorosis develops along margins, curl downward
plant remains small and lacks firmness (wilts)
no heads form

Remedies:
1. Foliar spray with 0.1%–0.2% solution of copper sulfate to which 0.5% hydrated lime has been added (not lettuce or leafy greens)
2. Add copper sulfate to nutrient solution

6. Manganese

Tomatoes
middle and older leaves – turn pale, later younger leaves also, characteristic checkered pattern of green veins and yellowish interveinal areas, later stages get small necrotic spots in pale areas, chlorosis less severe than in iron deficiency, also chlorosis is not confined to younger leaves as is the case with iron

Cucumbers
terminal or young leaves – yellowish interveinal mottling, at first even the small veins remain green, giving a reticular green pattern on a yellow background
progression – later, all except main veins turn yellow with sunken necrotic spots between the veins
shoots – stunted, new leaves remain small
older leaves – turn palest and die first

Peppers
similar to tomatoes above
leaves – checkered pattern of green veins, with interveinal tissue yellow green

Lettuce
leaves – interveinal tissue yellowish-green, veins remain green
leaves are smoother than normal
entire plant light green to yellow

Remedies:
1. Foliar spray using high-volume spray of 0.1% or low-volume spray of 1% solution of manganese sulfate (not lettuce or leafy greens)
2. Add manganese sulfate to nutrient solution

7. Molybdenum

Tomatoes
all leaves – leaflets show a pale green to yellowish interveinal mottling,

Cucumbers
older leaves – fade, particularly between veins, later leaves turn

TABLE 2.6 (Continued)
Summary of Mineral Deficiencies in Tomatoes, Cucumbers, Peppers, Lettuce and Remedies

margins curl upward to form a spout, smallest veins do not remain green, necrosis starts in the yellow areas, at the margins of the top leaflets and finally includes entire composite leaves which shrivel	pale green, finally yellow and die
progression – from the older to the younger leaves, but the cotyledons stay green for a long time	progression – from older leaves up to young leaves, youngest leaves remain green
	plant growth – normal, but flowers are small
Peppers	*Lettuce*
foliage – yellow-green	leaves – pale, distorted, narrow
growth – stunted	leaves whither from tip and margins inward
progression – from older to younger leaves	plants – stunted
Remedies:	root growth restricted
1. Foliar spray with 0.07%–0.1% solution of ammonium or sodium molybdate (not lettuce or leafy greens)	
2. Add ammonium or sodium molybdate to nutrient solution	

some abortion of flowers. Since the upper leaves are affected, the first choice is (AA). The terminal bud is alive; therefore, the next choice is (BB). The next decision is (C) versus (CC). Since chlorosis is present, but no wilting, the correct choice would be (CC). The alternative of (D) or (DD) can be made on the basis of the lack of dead spots. The proper choice is (DD). The choice between sulfur (E) versus iron (EE) is a little difficult. In the case of sulfur, the interveinal tissue is light green, not the bright yellow that appears with iron deficiency. The spindly stalks and flower abortion also indicate iron over sulfur deficiency. As a result, the final choice is iron deficiency.

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3 The Nutrient Solution

3.1 INORGANIC SALTS (FERTILIZERS)

In hydroponics, all the essential elements are supplied to the plants by dissolving fertilizer salts in water to make up the nutrient solution. The choice of salts to be used depends on a number of factors. The relative proportion of ions a compound will supply must be compared with that required in the nutrient formulation. For example, one molecule of potassium nitrate (KNO_3) will yield one ion of potassium (K^+) and one of nitrate (NO_3^-), whereas one molecule of calcium nitrate ($Ca(NO_3)_2$) will yield one ion of calcium (Ca^{2+}) and two ions of nitrate $2(NO_3^-)$. Therefore, if a minimum number of cations is required while supplying sufficient nitrate (anions) then calcium nitrate should be used; that is, half as much calcium nitrate as potassium nitrate would be required to satisfy the needs of the nitrate anion.

The various fertilizer salts that can be used for the nutrient solution have different solubilities (Appendix 4). Solubility is a measure of the concentration of the salt which will remain in solution when dissolved in water. If a salt has a low solubility, only small amounts of it will dissolve in water. In hydroponics, fertilizer salts having high solubility must be used since they must remain in solution to be available to the plants. For example, calcium may be supplied by either calcium nitrate or calcium sulfate. Calcium sulfate is cheaper, but its solubility is very low. Therefore, calcium nitrate should be used to supply the entire calcium requirements.

The cost of a particular fertilizer must be considered in deciding on its use. In general, a greenhouse grade should be used. The cost is somewhat greater than that of a standard grade, but the purity and solubility will be greater. A poor grade will contain a large amount of inert carriers (clay, silt particles), which can tie up nutrients and plug feeder lines. Regular grade calcium nitrate is bulk shipped to North America and packaged in this continent. For bulk shipping, it is coated with a greasy plasticizer to prevent it from accumulating water as it is hydroscopic (attracts water). Unfortunately, for use in nutrient solutions this greasy coating creates a thick scum that floats on the solution surface, plugs irrigation lines, and makes cleaning of tanks and equipment difficult. To avoid this problem, the special grade for greenhouse nutrient solutions called "Greenhouse Grade" should be used. It is packaged in a green and white bag, not the blue and red or red bags of the regular grades ("Viking Ship" brand). This is now called "YaraLiva" CALCINIT™ Greenhouse Grade, 15.50-0. The brand is now "Yara" with the Viking ship logo above.

The availability of nitrate versus ammonium compounds to plants is important in promoting either vegetative or reproductive growth. Plants can absorb both the cationic ammonium ion (NH_4^+) and the anion nitrate (NO_3^-). Ammonium, once absorbed, can immediately serve in the synthesis of amino acids and other compounds containing reduced nitrogen. Absorption of ammonium can therefore cause excessive vegetative growth, particularly under poor light conditions. Nitrate nitrogen, on the other hand, must be reduced before it is assimilated; therefore, vegetative growth will be held back. Ammonium salts could be used under bright summer conditions when photosynthetic rates are high or if nitrogen deficiency occurs and a rapid source of nitrogen is needed. In all other cases, nitrate salts should be used.

A summary of some salts which could be used for a hydroponic nutrient solution is given in Table 3.1. The particular choice of salt will depend on the above-mentioned factors and market availability. If a dry premix is to be used, such as in sawdust, peat, or vermiculite media, some of the more insoluble salts could be used, whereas if a nutrient solution is to be made up in advance, the more soluble compounds should be used (see footnote in Table 3.1). Potassium chloride and calcium

DOI: 10.1201/9781003133254-3

TABLE 3.1
Summary of Fertilizer Salts for Use in Hydroponics

Chemical Formula	Chemical Name	Mol. Wt.	Elements Supplied	Solubility Ratio of Solute to Water	Cost	Other Remarks
			A. Macroelements			
*KNO_3	Potassium Nitrate (Saltpeter)	101.1	K^+, NO_3^-	1:4	Low	Highly soluble, high purity.
*$Ca(NO_3)_2$	Calcium nitrate	164.1	Ca^{2+}, $2(NO_3^-)$	1:1	Low-medium	Highly soluble, but is with a greasy plasticizer coat – must be skimmed off nutrient solution – use Greenhouse Grade.
$(NH_4)_2SO_4$	Ammonium sulphate	132.2	$2(NH_4^+)$, SO_4^{2-}	1:2	Medium	These ammonium
$NH_4H_2PO_4$	Ammonium dihydrogen phosphate	115.0	NH_4^+, $H_2PO_4^-$	1:4	Medium	compounds should be used only under very good light conditions
NH_4NO_3	Ammonium nitrate	80.05	NH_4, NO_3^-	1:1	Medium	or to correct N-deficiencies.
$(NH_4)_2HPO_4$	Ammonium monohydrogen phosphate	132.1	$2(NH_4^+)$, HPO_4^{2-}	1:2	Medium	
*KH_2PO_4	Monopotassium phosphate	136.1	K^+, $H_2PO_4^-$	1:3	Very costly	An excellent salt, highly soluble and pure, but costly.
KCl	Potassium chloride (Muriate of potash)	74.55	K^+, Cl^-	1:3	Costly	Should only be used for K-deficiencies and when no sodium chloride is present in nutrient solution.
*K_2SO_4	Potassium sulfate	174.3	$2K^+$, SO_4^{2-}	1:15	Low	It has low solubility, now soluble grades available.
$Ca(H_2PO_4)_2$	Monocalcium phosphate	252.1	Ca^{2+}, $2(H_2PO_4^-)$	1:60	Low	Very difficult to obtain a soluble grade.
$CaH_4(PO_4)_2$	Triple super phosphate	Variable	Ca^{2+}, $2(PO_4^{2-})$	1:300	Low	Very low solubility, good for dry pre-mixes, not for nutrient solutions.
*$MgSO_4.7H_2O$	Magnesium sulfate (Epsom salts)	246.5	Mg^{2+}, SO_4^{2-}	1:2	Low	Excellent, cheap, highly soluble, pure.
$CaCl_2.2H_2O$	Calcium chloride	147.0	Ca^{2+}, 2Cl	1:1	Expensive	Highly soluble, good to overcome Ca-deficiencies, but use only if no NaCl present in nutrient solution.

$CaSO_4.2H_2O$	Calcium sulfate (Gypsum)	172.2	Ca^{2+}, SO_4^{2-}	1:500	Low	Very insoluble, cannot use for nutrient solutions.
H_3PO_4	Phosphoric acid (Orthophosphoric acid)	98.0	PO_4^{3-}	Concentrated acid solution	Expensive	Good use in correction of P-deficiencies.
			B. Microelements			
$FeSO_4.7H_2O$	Ferrous sulfate (Green vitriol)	278.0	Fe^{2+}, SO_4^{2-}	1:4		
$FeCl_3.6H_2O$	Ferric chloride	270.3	Fe^{3+}, $3Cl^-$	1:2		
*FeDTPA	Iron chelate (Sprint 330) (10% iron)	468.15	Fe^{2+}	Highly soluble	Expensive	Best source of iron; dissolve in hot water.
*FeEDTA	Iron chelate (Sequestrene) (10.5% iron)	382.1	Fe^{2+}	Highly soluble	Expensive	Good source of iron, but FeDTPA is better.
*H_3BO_3	Boric acid	61.8	B^{3+}	1:20	Expensive	Best source of boron; dissolve in hot water.
$Na_2B_8O_{13}.4H_2O$	Disodium octa-borate tetrahydrate (Solubor)	412.52	B^{3+}	Very soluble	Inexpensive	
$Na_2B_4O_7.10H_2O$	Sodium tetra-borate (Borax)	381.4	B^{3+}	1:25		
*$CuSO_4.5H_2O$	Copper sulfate (Bluestone)	249.7	Cu^{2+}, SO_4^{2-}	1:5	Inexpensive	
*$MnSO_4.4H_2O$	Manganese sulfate	223.1	Mn^{2+}, SO_4^{2-}	1:2	Inexpensive	
$MnCl_2.4H_2O$	Manganese chloride	197.9	Mn^{2+}, 2Cl	1:2	Inexpensive	
*$ZnSO_4.7H_2O$	Zinc sulfate	287.6	Zn^{2+}, SO_4^{2-}	1:3	Inexpensive	
$ZnCl_2$	Zinc chloride	136.3	Zn^{2+}, $2Cl^-$	1:1.5	Inexpensive	
$(NH_4)_6Mo_7O_{24}$	Ammonium molybdate	1163.8	NH_4^+, Mo^{6+}	1:2.3 Highly soluble	Moderately expensive	
Na_2MoO_4	Sodium molybdate	205.92	$2Na^+$, Mo^{6+}	Highly soluble	Moderately expensive	
*ZnEDTA	Zinc chelate	431.6	Zn^{2+}	Highly soluble	Expensive	
*MnEDTA	Manganese chelate	381.2	Mn^{2+}	Highly soluble	Expensive	

* These more soluble compounds should be used for preparing nutrient solutions.

chloride should be used only to correct potassium and calcium deficiencies, respectively. These, however, can be used only if insignificant amounts of sodium chloride (less than 50–100 ppm) are present in the nutrient solution. If chlorides are added in the presence of sodium, poisoning of the plants will result.

The use of chelates (of iron, manganese, and zinc) is highly recommended since they remain in solution and are readily available to plants even under *p*H shifts. A chelated salt is one having a soluble organic component to which the mineral element can adhere until uptake by the plant roots occurs. The organic component is ethylenediaminetetra acetic acid (EDTA). EDTA has a high affinity for calcium ions and is thus a poor chelating agent for calcareous media (limestone, coral sand). In this case, it should be replaced with ethylenediamine dihydroxyphenylacetic acid (EDDHA). Iron can be supplied from the iron salt of sodium ferric diethylenetriamine pentaacetate (DTPA). This salt is abbreviated Fe-DP and has 7% iron. A good make is "Sprint 330" from "Becker Underwood," which has 10% iron chelated to DTPA.

3.2 RECOMMENDED COMPOUNDS FOR COMPLETE NUTRIENT SOLUTIONS

Calcium nitrate that provides both calcium and nitrate nitrogen should be used. Any additional nitrogen required should be provided by potassium nitrate, which also provides potassium. All phosphorus may be obtained from monopotassium phosphate, which also provides some potassium. The remaining potassium requirement can be obtained from potassium sulfate, which also supplies some sulfur. Additional sulfur comes from other sulfates such as magnesium sulfate, which supplies the magnesium needs.

Micronutrients may be obtained from commercial premixes. While these are relatively expensive, they save the substantial labor of weighing the individual compounds contained in the mix.

Hobby growers may wish to use premixes for the macronutrients, but commercial growers should use the basic compounds listed in Table 3.1. This is because it is very difficult to get a homogeneous mixture of fertilizers when hundreds of pounds of individual compounds are blended with a mechanical mixer. Many of the compounds are in powder or fine grain form, and often lumpy, which do not mix evenly mechanically. Experience with such premixes has revealed shortages in magnesium, almost always a shortage of iron and, often, excesses of manganese. In addition, premixes do not offer flexibility in manipulating a nutrient formulation, which is necessary during different stages of plant growth and under changing sunlight hours and day length. This ability to make changes in the nutrient formulation is imperative in the optimization of crop yields.

3.3 FERTILIZER CHEMICAL ANALYSES

The amounts of available nitrogen, phosphorus, and potassium are given on fertilizer bags as the percentage of nitrogen (N), phosphoric anhydride (P_2O_5), and potassium oxide (K_2O). It has traditionally been expressed in these terms, not in percentage of N, P, or K alone. For example, potassium nitrate is given as 13-0-44, indicating 13% N, 0% P_2O_5, and 44% K_2O.

Nutrient formulations for hydroponics express nitrogen as N, NH_4^+, or NO_3^-; phosphorus as P or PO_4^{3-}, not P_2O_5; and potassium as K^+, not K_2O. Therefore, it is necessary to convert N to NO_3^-, P_2O_5 to P or PO_4^{3-}, and K_2O to K^+ or vice versa in each case. Conversions of this nature can be made by calculating the fraction of each element within its compound source. Table 3.2 lists conversion factors to determine the fraction of an element within a compound and vice versa. It was derived by the use of atomic and molecular weights as follows: the fraction of N in NO_3^- is the atomic weight of nitrogen (14) divided by the molecular weight of nitrate (62), which is 14/62 = 0.226. In Table 3.2, this factor is listed in the second line under the column conversion factor B to A. That is because we have nitrate and want to find the amount of nitrogen in it. To determine the amount of nitrate needed

TABLE 3.2
Conversion Factors for Fertilizer Salts

Column A*	Column B*	Conversion Factor A to B	Conversion Factor B to A
Nitrogen (N)	Ammonia (NH_3)	1.216	0.822
	Nitrate (NO_3)	4.429	0.226
	Potassium nitrate (KNO_3)	7.221	0.1385
	Calcium nitrate ($Ca(NO_3)_2$)	5.861	0.171
	Ammonium sulfate ($(NH_4)_2SO_4$)	4.721	0.212
	Ammonium nitrate (NH_4NO_3)	2.857	0.350
	Diammonium phosphate ($(NH_4)_2HPO_4$)	4.717	0.212
Phosphorus (P)	Phosphoric anhydride (P_2O_5)	2.292	0.436
	Phosphate (PO_4)	3.066	0.326
	Monopotassium phosphate (KH_2PO_4)	4.394	0.228
	Diammonium phosphate ($(NH_4)_2HPO_4$)	4.255	0.235
	Phosphoric acid (H_3PO_4)	3.164	0.316
Potassium (K)	Potash (K_2O)	1.205	0.830
	Potassium nitrate (KNO_3)	2.586	0.387
	Monopotassium phosphate (KH_2PO_4)	3.481	0.287
	Potassium chloride (KCl)	1.907	0.524
	Potassium sulfate (K_2SO_4)	2.229	0.449
Calcium (Ca)	Calcium oxide (CaO)	1.399	0.715
	Calcium nitrate ($Ca(NO_3)_2$)	4.094	0.244
	Calcium chloride ($CaCl_2.2H_2O$)	3.668	0.273
	Calcium sulfate ($CaSO_4.2H_2O$)	4.296	0.233
Magnesium (Mg)	Magnesium oxide (MgO)	1.658	0.603
	Magnesium sulfate ($MgSO_4.7H_2O$)	10.14	0.0986
Sulfur (S)	Sulfuric acid (H_2SO_4)	3.059	0.327
	Ammonium sulfate ($(NH_4)_2SO_4$)	4.124	0.242
	Potassium sulfate (K_2SO_4)	5.437	0.184
	Magnesium sulfate ($MgSO_4.7H_2O$)	7.689	0.130
	Calcium sulfate ($CaSO_4.2H_2O$)	5.371	0.186
Iron (Fe)	Ferrous sulfate ($FeSO_4.7H_2O$)	4.978	0.201
	Iron chelate (10% iron) (FeEDTA)/(FeDTPA)	10.00	0.100
Boron (B)	Boric acid (H_3BO_3)	5.717	0.175
	Sodium tetraborate (Borax) ($Na_2B_4O_7.10H_2O$)	8.820	0.113
	Disodium octaborate (Solubor) ($Na_2B_8O_{13}.4H_2O$)	4.770	0.210
Copper (Cu)	Copper sulfate ($CuSO_4.5H_2O$)	3.930	0.254
Manganese (Mn)	Manganese sulfate ($MnSO_4.4H_2O$)	4.061	0.246
	Manganese chloride ($MnCl_2.4H_2O$)	3.602	0.278
	Manganese chelate (5% liquid) ($Mn(NH_4)_2EDTA$)	20.00	0.050
Zinc (Zn)	Zinc sulfate ($ZnSO_4.7H_2O$)	4.400	0.227
	Zinc chloride ($ZnCl_2$)	2.085	0.480
	Zinc chelate (14% powder) (ZnEDTA)	7.143	0.140
	Zinc chelate (9% liquid) (ZnEDTA)	11.11	0.090
Molybdenum (Mo)	Ammonium molybdate ($(NH_4)_6Mo_7O_{24}$)	1.733	0.577
	Sodium molybdate (Na_2MoO_4)	2.146	0.466

* To convert from an element (column A) to the compound supplying it (column B), use conversion factor A to B. To determine amounts of an element (column A) present in a compound (column B), multiply by factor B to A. These factors are derived from the fraction of an element present in a compound based on the atomic weight of the element and molecular weight of the compound.

for a unit of nitrogen, the reciprocal (inverse) of the fraction is used as the following ratio is applied and solved for "x."

$$\begin{array}{cc} 1 & x \\ N & NO_3 \\ 14 & 62 \end{array}$$

Cross multiply we get:

$$14x = 62$$

Therefore,

$$x = 62/14 = 4.429$$

This is the conversion factor A to B in the second line of Table 3.2. Understanding this concept for the derivation of these factors will enable you to calculate other factors, should compounds other than those appearing in Table 3.2 be used.

3.4 FERTILIZER IMPURITIES

Most fertilizer salts are not 100% pure. They often contain inert "carriers" such as clay, silt, and sand particles, which do not supply ions. Therefore, percentage purity or a guaranteed analysis is often given on the fertilizer bag. The percentage purities of some fertilizers are given in Table 3.3. These impurities must be taken into consideration when calculating the fertilizer requirements for a particular nutrient formulation.

Many fertilizers have synonyms or common names. A list of these common names is given in Table 3.4.

TABLE 3.3
Percentage Purities of Commercial Fertilizers

Salt	% Purity
Ammonium phosphate ($NH_4H_2PO_4$) (food grade)	98
Ammonium sulfate ($(NH_4)_2SO_4$)	94
Ammonium nitrate, pure (NH_4NO_3)	98
Calcium nitrate ($Ca(NO_3)_2$)	90
Calcium chloride ($CaCl_2.2H_2O$)	77
Calcium sulfate ($CaSO_4$) (Gypsum)	70
Monocalcium phosphate ($Ca(H_2PO_4)_2$) (food grade)	92
Monopotassium phosphate (KH_2PO_4)	98
Magnesium sulfate ($MgSO_4.7H_2O$)	98
Potassium nitrate (KNO_3)	95
Potassium sulfate (K_2SO_4)	90
Potassium chloride (KCl)	95

The purity is calculated on the basis of the designated formula. Water of crystallization is not considered as impurity. Always check the percentage purity on the bag as it varies with different manufacturers.

Note that in Table 3.2, the water of crystallization has been accounted for in the calculations of the conversion factors.

TABLE 3.4
Chemical Names and Synonyms of Compounds Generally Used in Nutrient Solutions

Chemical Name	Synonyms or Common Name
Potassium nitrate KNO_3	Saltpeter.
Sodium nitrate $NaNO_3$	Chile saltpeter; niter; Chile niter.
Ammonium acid phosphate $NH_4H_2PO_4$	Ammonium biphosphate; ammonium bihydrogenphosphate; monobasic ammonium phosphate.
Urea $CO(NH_2)_2$	Carbamide; carbonyldiamide.
Potassium sulfate K_2SO_4	Sulfate of potash.
Potassium acid phosphate KH_2PO_4	Potassium biphosphate; potassium dihydrogen phosphate; monobasic potassium phosphate.
Potassium chloride KCl	Muriate of potash; chloride of potash.
Monocalcium phosphate $Ca(H_2PO_4)_2H_2O$	Calcium "superphosphate" (usually 20% pure); calcium "treble superphosphate" (usually 75% pure); calcium biphosphate; calcium acid phosphate.
Phosphoric acid H_3PO_4	Orthophosphoric acid (U.S.P. grade is 85–88% H_3PO_4; commercial technical grade is 70–75% H_3PO_4).
Calcium sulfate $CaSO_4.2H_2O$	Gypsum.
Calcium chloride $CaCl_2.2H_2O$	Calcium chloride dihydrate. Also available as hexahydrate ($CaCl_2.6H_2O$).
Magnesium sulfate $MgSO_4.7H_2O$	Epsom salts.
Ferrous sulfate $FeSO_4.7H_2O$	Green vitriol; iron vitriol.
Zinc sulfate $ZnSO_4.7H_2O$	White or zinc vitriol.
Boric acid H_3BO_3	Boracic acid; orthoboric acid.
Copper sulfate $CuSO_4.5H_2O$	Cupric sulfate; bluestone.

Source: Adapted from Withrow, R.B. and A.P. Withrow, *Nutriculture*. Purdue University Agricultural Experimental Station Publication, S.C. 328, Lafayette, IN, 1948.

3.5 ORGANIC FERTILIZERS

Hydroponic organic certified growing has become popular due to the added value of organically grown produce. However, it is more complex than using traditional inorganic fertilizers. There are very few hydroponic organic growers. They are small operations and generally grow leafy crops such as lettuce, leafy greens, and herbs. These crops tolerate higher levels of ammonium-based nitrogen in the form of proteins that break down into their amino acid constituents. Tomatoes and other fruiting vine crops are much more challenging, as they prefer no more than 10% of their total nitrogen source from an ammonium source. A large portion of the total nitrogen requirement in the

form of ammonium promotes rapid vegetative growth over the generative fruiting phase. As a result, it is very difficult to manage the growing phases of the fruiting plants. The plants will therefore remain vegetative, yielding few fruit.

Another important factor of using organic fertilizers is their variation and inaccuracies of true N-P-K and other element constituents. There is so much variation in the actual amounts of all of the elements compared to the stated "guaranteed analysis" that the lack of consistency makes composing a specific nutrient formulation over time very difficult. Any solution makeup based upon previous weights of the organic fertilizers used can result in changes in the actual concentrations of individual elements compared to those theoretically calculated. This lack of consistent levels of nutrients in the organic source fertilizers causes extreme difficulty in managing an optimum nutrient solution over the cropping cycle.

A third factor is the difficulty in making up a nutrient formulation having the correct ratios and concentrations of individual elements. While products, such as Epsom salts (magnesium sulfate) have organic certification, other essential elements such as calcium in the form of calcium nitrate are not certified organic and therefore cannot be used for organic certified products. As a result, it is very difficult to meet the calcium nutrient levels needed in hydroponic formulations. Most microelements are available in organic forms.

3.5.1 Recommended Organic Compounds

Research is needed of the Organic Materials Review Institute (OMRI) to determine what fertilizers have organic certification. Their search site www.omri.org/omri-search gives the status of fertilizer sources as to whether they are certified for organic growing. The site gives listings of approved products for the United States, Canada, and Mexico. It states the category of product, use restrictions, and the company manufacturing the product. There are hundreds of products. There are many products suitable to growing in the soil, but not in hydroponics due to impurities, insoluble constituents causing sludge in nutrient tanks, and strong odors. For example, animal manures, seabird and bat guanos, fish meal and emulsions, shellfish fertilizer and meal, aquatic plant and seaweed extracts all have odors and do not dissolve into a water solution, but only a suspension. Many of these need microbial breakdown in the soil. Such microbial breakdown is very slow and would not occur in a sterile hydroponic system. For this reason, most organic fertilizers are not suitable for hydroponics as their release of elements is very slow. There are many prepared blends for hydroponics. The main constituents of blends are liquid extracts from the sources mentioned above. Some have added minerals from rock phosphate, green sand limestone, and other mined minerals and their derivatives. Some forms of sulfate of potash (K_2SO_4), calcium sulfate from gypsum, and magnesium sulfate are organic certified. These will add potassium, sulfur, calcium, and magnesium. However, with the exception of magnesium sulfate, which is soluble, the others are very insoluble. The majority of these blends were developed for growing cannabis. Table 3.5 is a summary of common products that could be used for some hydroponic crops.

Most of the above blended organic fertilizers must be combined over the growth cycle of the plants. The manufacturers provide detailed schedules for using each of the fertilizers during various stages of cannabis plant growth. They do not provide schedules for other crops.

There are many fertilizers, especially liquid forms, which state they are organically based, but these may not have OMRI certification. To grow organically certified vegetables only OMRI certified products may be used. An OMRI logo is printed on the package or container if it is OMRI certified.

The most difficult step is to put a combination of these products together to meet a nutrient formulation. The granular products have limited solubility, so are slow in releasing their elements.

TABLE 3.5
Summary of Organic Fertilizers for Hydroponics

*Product	**N:P:K	Elements Provided	Rate	Remarks
Crop: Cannabis				
General Hydroponics-BioThrive Grow	NA	H_3PO_4 (5–10%) + Humic Acid (1–3%)	5-10 mL/US gal	Vegetative
GH-BioThrive Bloom	NA	H_3PO_4 (5–10%) + Humic Acid (1–3%)	10 mL/US gal	Flower
GH-CaMg	NA	Ca + Mg	5 mL/US gal	All stages
GH-BioRoot	NA	H_3PO_4 (1–3%)	10 mL/US gal	Roots
GH-BioBud	NA	None given	2.5 mL/US gal	Buds
The above are all combined at different stages of the plant growth according to General Hydroponics feed chart.				
Fox Farm Big Bloom (bat guano + earthworm castings)	0-0.5-0.7	N,P,K	60–120 mL/4 L.	Vegetative phase
Fox Bush Doctor Liquid Iron	1-0-0 + 5%	iron	1.25–2.5 mL/ 4 L.	All growth
Fox Bush Doctor Kelp Me Kelp You (seaweed extract)	0.5-0-0.5	N,K	5–10 mL/4 L.	Vegetative
Fox Bush Doctor Wholly Mackerel (fish extract)	3-1-0	N,P	15 mL/4 L.	Vegetative
The following may not be OMRI approved:				
Fox Cultivation-Grow	2-1-6	N,P,K	15 mL/4 L.	Vegetative
Fox Cultivation-Micro	5-0-1	N,K, + Micros	5–10 mL/4 L.	Flower
Fox Cultivation-Bloom	0-5-4	P,K	10–12.5 mL/4 L.	Bud
Fox Tiger Bloom	2-8-4	N,P,K + Micros	10–20 mL/4 L.	Flower
For vegetable crops:				
Dr. Earth All Purpose (fish bone meal, alfalfa meal, fish meal, kelp meal, K_2SO_4, bacillus and mycorrhizae)	4-6-5	N,P,K + 5% Humic Acid		Granular form suitable for soilless media at soil rates
Dr. Earth Home Grown Tomato, Vegetable & Herb (sources as for All Purpose)	5-7-3	N,P,K, 8% Ca, 1% Mg, 2% S + 6% Humic Acid		Granular – as above
Pro-Mix Multi-Purpose Garden Fertilizer	7-3-3	N,P,K, + mycorrhizae		Granular – as above
Pro-Mix Organic Tomatoes, Vegetables	4-4-8	N,P,K, + mycorrhizae		Granular – as above
Down to Earth All Purpose	4-6-2	N,P,K, 10% Ca, 1% Mg, 2% S, 2.5% Humic Acid		Granular – as above
Down to Earth Vegan Mix	3-2-2	N,P,K, 4% Ca, 1% Mg, 2.5% Humic Acid		Granular – as above
Down to Earth Vegetable Garden	4-4-4	N,P,K, 6% Ca, 1% Mg, 0.4% Fe		Granular – as above

(*continued*)

TABLE 3.5 (Continued)
Summary of Organic Fertilizers for Hydroponics

*Product	**N:P:K	Elements Provided	Rate	Remarks
Down to Earth Garden Gypsum	0-0-0	21% Ca, 17% S		Prilled – as above
Down to Earth Calcium 96	0-0-0	38% Ca, 0.5% $MgCO_3$		Limestone powder
Down to Earth Bio-Live	5-4-2	N,P,K, 2.5% Humic Acid, mycorrhizae, Bacillus		Granular
Jobe's Organics All Purpose	5-2-3	N,P,K, Bacillus, mycorrhizae		Water Soluble
Live Earth First Green	5-3-1	N,P,K, 4% Ca, 5% S, 1% Fe, 21% Humic Acid		Granular
(humic shale, soft rock phosphate, ammonium sulfate, potassium sulfate) (no OMRI logo, but constituents are organic certified)				
Age Old Grow In Full Bloom	5-10-5	N,P,K, 1% Ca, Humic Acid		Granular
The label indicates not to use for organic certified products.				
Organicare Pure Grow	6-6-5	N,P,K, 8% Ca, 3% Humic Acid		Granular
Organicare Pure Bloom	1-5-4	N,P,K, 6% Ca		Granular
Dr. Iron (derived from elemental sulfur and iron oxide) (OMRI approved)	0-0-0	22% Fe, 55% S		Granular
EZ-Gro Organic Powder	9-1.5-7	N,P,K, 4.5% Ca, 1% Mg, 0.32% Mn, 0.35% Zn, 0.0875% B, 0.125% Cu, 0.2% Fe		Powder
EZ-Gro Organic Calcium-Magnesium	0-0-0	4% Ca, 1.65% Mg, 3% Humic Acid		Powder
EZ-Gro has many OMRI approved products in liquid and powder forms.				

* Only a few common organic fertilizers are given here as an example of such products. There are many such products. It is necessary to check with OMRI sources to determine whether they are certified organic.

** N:P:K is ratio of N: P_2O_5: K_2O and is generally expressed in percentages. These percentages also vary with product manufacturer and different batches from the same source.

Therefore, they should only be used with a soilless substrate. A possible combination of some of these is as follows:

1. Organicare Pure Grow (6-6-5 + 8% Ca + 3% humic acid)
2. Magnesium sulfate (OMRI form)

3. Age Old Calcium 20%
4. Dr. Iron 22% iron
5. Down to Earth Liquid MicroNutrient (2-0-1) (2% Fe, 2% Mn, 2% Zn plus Boron and copper
6. Potassium sulfate if needed to increase K level

Alternative: EZ-Gro Organic Powder Grow 9-1.5-7

Rate: 2 gm per liter of water.

Phosphorus needs to be added. Possibly EZ-Gro Phosphorus Suspension with 3% P_2O_5 and 6% Ca could be used.

Composing an optimum nutrient formulation from these certified organic products is very complex and requires trials with various combinations. Most are suitable to a soilless substrate as they can be incorporated into the medium as they would with soil growing. To formulate a liquid nutrient solution for other hydroponic systems would be more complex requiring trials, laboratory analyses of the nutrient solution, and continued adjustments in the solution components. However, when accomplished the certified organic product would receive a much higher market value than non-organic products.

3.6 NUTRIENT FORMULATIONS

Nutrient formulations are usually given in parts per million (ppm) concentrations of each essential element. One part per million is one part of one item in 1 million parts of another. It may be a weight measure, for example, 1 *u*g/g, a weight–volume measure, for example, 1mg/L or a volume–volume measure, for example, 1 *u*L/L. Proofs for these are as follows:

$$1\ ug/g = \frac{1/1{,}000{,}000}{1g}g = \frac{1}{1{,}000{,}000}g$$

$$1\ uL/L = \frac{1/1{,}000{,}000}{1L}l = \frac{1}{1{,}000{,}000}L$$

$1\,mg/L$:

$$1\ mg = 1/1000\,g, \qquad 1L = 1{,}000\,mL$$

Therefore:

$$1\,mg/L = \frac{1/1{,}000\ g}{1{,}000\,mL\ H_2O} = \frac{1}{1{,}000{,}000}g \qquad \begin{matrix}\text{Since}\,1\,mL\,\text{of}\,H_2O\\ \text{weighs 1 g}\end{matrix}$$

3.6.1 Atomic and Molecular Weights

Atomic and molecular weights of elements and compounds, respectively, must be used in calculating nutrient formulation concentration requirements. Atomic weights indicate the relative weights of different atoms, that is, how the weight of one atom compares with that of another. Tables of atomic weights for every atom have been drawn up by establishing a relative scale of atomic weights. In doing so, one element is chosen as the standard and all other elements are compared with it. Oxygen (O) has been assigned an atomic weight of exactly 16, and all other elements are related to it. Table 3.6 lists the atomic weights of elements commonly used in hydroponics.

When a number of atoms combine they form a molecule, which is expressed using a molecular formula. For example, water is represented as H_2O and consists of two atoms of hydrogen (H) and one atom of oxygen (O). The weight of any compound is the molecular weight, which is simply the sum of the weights of the atoms in the molecule. The molecular weight of water is 18 (there are two atoms of hydrogen, each having atomic weight of 1.00, and one atom of oxygen having an atomic weight of 16.0). Molecular weights of commonly used fertilizers for hydroponics are given in Table 3.1. The atomic weights of all known elements are given in tables and periodic charts of chemistry texts.

The following examples will clarify the use of atomic and molecular weights in nutrient formulation calculations:

Calcium nitrate – $Ca(NO_3)_2$

Atomic weight:	**Molecular weight:**
Ca = 40.08	Ca = 40.08
N = 14.008	2N = 28.016
O = 16.00	6O = 96.0
	164.096

Note: There are two nitrogen atoms and six oxygen atoms in calcium nitrate.

3.6.2 Calculations of Nutrient Formulations

If a nutrient formulation calls for 200 ppm of calcium (200 mg/L) we need 200 mg of calcium in every liter of water. In 164 mg of $Ca(NO_3)_2$ we have 40 mg of Ca [using the atomic and molecular weights to determine the fraction of calcium in calcium nitrate – assuming 100% purity of $Ca(NO_3)_2$]. The first step is to calculate how much $Ca(NO_3)_2$ is required to obtain 200 mg of Ca. This is done by setting up a ratio as follows:

164 mg $Ca(NO_3)_2$ yields 40 mg Ca
x mg $Ca(NO_3)_2$ yields 200 mg Ca
Ratio of Ca/$Ca(NO_3)_2$: 40/164 = 200/x

Solving for x:

40 x = 200 x 164 (cross multiply)
x = 200 x 164/40 = 820

Therefore, 820 mg of $Ca(NO_3)_2$ will yield 200 mg Ca. If the 820 mg of $Ca(NO_3)_2$ is dissolved in 1 liter of water, the resultant solution will have a concentration of 200 ppm (200 mg/L) of Ca. This assumes, however, that the $Ca(NO_3)_2$ is 100% pure. If it is not – which is usually the case – it will be necessary to add more to compensate for the impurity. For example, if the $Ca(NO_3)_2$ is 90% pure, it will be necessary to add

100/90 x 820 = 911 mg $Ca(NO_3)_2$

Hence, 911 mg $Ca(NO_3)_2$ in 1 L of water will give 200 ppm of Ca.

Of course, in most cases a volume of nutrient solution larger than 1 L will be required. The second step, then, is to calculate the amount of fertilizer required for a given volume of nutrients.

TABLE 3.6
Atomic Weights of Elements Commonly Used in Hydroponics

Name	Symbol	Atomic Wt.
Aluminum	Al	26.98
Boron	B	10.81
Calcium	Ca	40.08
Carbon	C	12.01
Chlorine	Cl	35.45
Copper	Cu	63.54
Hydrogen	H	1.008
Iron	Fe	55.85
Magnesium	Mg	24.31
Manganese	Mn	54.94
Molybdenum	Mo	95.94
Nitrogen	N	14.01
Oxygen	O	16.00
Phosphorus	P	30.97
Potassium	K	39.10
Selenium	Se	78.96
Silicon	Si	28.09
Sodium	Na	22.99
Sulfur	S	32.06
Zinc	Zn	65.37

Initially, calculate the amount of a compound needed using the metric system of milligrams per liter, then convert to pounds per gallon, if necessary. First, convert the volume of the nutrient tank in gallons to liters. To do this, be aware that there is the following difference between Imperial gallons (British system) and US gallons:

1 US gallon (gal) = 3.785 L
1 Imperial gallon (gal) = 4.5459 L
Hence, 100 US gal = 378.5 L
100 Imperial gal = 454.6 L

The solution to the following problem will demonstrate the use of these conversions. Assume that a 200-ppm concentration of Ca is required in a 300-US-gal nutrient tank.

$$300 \text{ US gal} = 300 \times 3.785 \text{ L} = 1{,}135.5 \text{ L}$$

If 911 mg $Ca(NO_3)_2$ are required per liter of water, the amount needed for 300 US gal would be

$$911 \text{ mg} \times 1{,}135.5 \text{ L} = 1{,}034{,}440 \text{ mg}$$

To convert to grams, divide by 1,000 as 1,000 mg = 1 g

$$\frac{1{,}034{,}440\,\text{mg}}{1{,}000\,\text{mg}} = 1{,}034.4\,\text{g}$$

Now, convert to kilograms by dividing by 1,000 as 1,000 g = 1 kg

$$\frac{1,034,4\,\text{g}}{1,000\,\text{g}} = 1,034\ \text{kg}$$

To calculate in pounds, use either 1 lb = 454 g or 1 kg = 2.2046 lb

Therefore,

$$\frac{1,034,4}{454\,\text{g}}\,\text{g} = 2.278\ \text{lb} = 2.28\ \text{lb}$$

or

$$1.034\ \text{kg} \times 2.2046\ \text{lb} = 2.28\ \text{lb}$$

Then, convert the fraction of pounds to ounces using 1 lb = 16 oz.

$$2\ \text{lb} + (0.28\ \text{lb} \times 16 = 4.5\ \text{oz})\ \text{That is, 2 lb 4.5 oz.}$$

While this conversion to pounds is precise enough for larger weights, anything under a pound should be weighed in grams for more accuracy. A suitable gram scale for most weighing under 1 lb is a triple-beam balance that is accurate to 0.1 g.

If the compound used contains more than one essential element – this is the usual case – the third step is to determine how much of each of the other elements was added when satisfying the needs of the first essential element. Calcium nitrate contains both calcium and nitrogen. Therefore, the third step is to calculate the amount of nitrogen added while satisfying the calcium needs.

This should be done using the ppm concept so that adjustments can be made for this element. The calculation is done using the fraction of nitrogen in calcium nitrate and multiplying the amount of calcium nitrate used by this fraction. Use the weight of calcium nitrate before adjustments for impurities, that is, 820 mg not 911 mg, as follows:

$$\frac{2(14)}{164} \times 820\ \text{mg/L} = 140\,\text{mg/L}\ \ (\text{ppm})$$

In summary, 820 mg/L of calcium nitrate will yield 200 mg/L of calcium and 140 mg/L of nitrogen (assuming 100% purity). Further, using the example for a 300-US-gal tank, 2 lb 4.5 oz (1,034 g) of calcium nitrate provides 200 ppm of calcium and 140 ppm of nitrogen in the tank of solution.

Using the conversion factors in Table 3.2, the calculations may be simplified. The atomic and molecular weights and their fractions need not be used, as that is how the conversion factors of Table 3.2 were derived as explained earlier.

Going back to step one to determine the amount of calcium nitrate needed to supply 200 ppm (mg/L) of calcium, use the conversion factor in Table 3.2. We want 200 ppm of Ca from the source $Ca(NO_3)_2$. Use the factor A to B of 4.094

$$200 \times 4.094 = 819\ \text{mg/L of}\ Ca(NO_3)_2$$

Note that there is a slight difference between this value and the previous one (819 mg/L vs. 820 mg/L). This small difference is insignificant for our purposes.

Similarly, the amount of nitrogen in 819 mg/L of calcium nitrate may be calculated using conversion factor B to A of 0.171 in Table 3.2:

$$0.171 \times 819 \text{mg/L} = 140 \text{ mg/L (ppm) of N}$$

The fourth step is to calculate the additional amount of the second element needed from another source. For example, if the nutrient formulation asked for 150 ppm of N, the additional requirement would be

$$150 - 140 = 10 \text{ ppm of N}$$

This could be obtained from KNO_3. Then the amount of KNO_3 needed to supply 10 ppm of N using the conversion factor A to B of 7.221 in Table 3.2 would be

$$7.221 \times 10 = 72.21 \text{ mg/L of } KNO_3$$

Since KNO_3 also contains potassium (K), we must calculate the amount present using conversion factor B to A of 0.387 (Table 3.2):

$$0.387 \times 72.21 \text{ mg/L} = 28 \text{ mg/L (ppm) of K}$$

To determine the amount of KNO_3 needed for a 300-US-gal nutrient tank to provide 10 ppm of N, the following calculations must be done:

1. Adjust for impurity from Table 3.3 (95% pure):
   100/95 x 72.21 mg/L = 76 mg/L
2. The volume of a 300-US-gal tank is obtained as
   300 x 3.785 L = 1,135.5 L
3. Therefore, the amount of KNO_3 needed is given by
   1,135.5 L x 76 mg/1000 mg = 86.3 g

This weight may be kept in grams as it is under 1 lb, or it may be converted to ounces.

4. Since 1 oz = 28.35 g
   86.3 g/28.35 g = 3.0 oz

Note that measurements in grams are more accurate than those in ounces.

These calculations may be continued for all the essential elements. The types and quantities of the various fertilizer salts must be manipulated until the desired formulation is achieved.

In some cases a problem may arise if the requirements of one element are satisfied by use of a compound which contains two or more essential elements, but the concentration of another element exceeds the level required.

For instance, if the nutrient formulation called for 300 ppm Ca and 150 ppm N, the calcium supplied by calcium nitrate can be calculated as follows:

1. Weight of $Ca(NO_3)_2$ needed (use Table 3.2 conversion factors):
   300 ppm (mg/L) x 4.094 = 1,228 mg/L
2. Amount of N added:
   1,228 mg/L x 0.171 = 210 mg/L (ppm) N

This gives an excess of 60 ppm of N over the recommended 150 ppm N given in the formulation. Therefore, the level of N will govern the amount of $Ca(NO_3)_2$ that can be used as a source of Ca. The previous steps must be recalculated using the limit of 150 ppm N:

1. Weight of $Ca(NO_3)_2$ needed (use factors of Table 3.2):
   150 ppm (mgL) x 5.861 = 879 mg/L
2. Amount of Ca added:
   879 mg/L x 0.244 = 214 mg/L (ppm) Ca

If the recommended level of Ca is 300 ppm, then (300-214) = 86 ppm Ca must be supplied from sources other than $Ca(NO_3)_2$. Since calcium sulfate ($CaSO_4$) is very insoluble, the only alternative is to use calcium chloride ($CaCl_2.2H_2O$). Note the water of crystallization in calcium chloride. This has been taken into account in calculating the conversion factors in Table 3.2.

3. Weight of $CaCl_2.2H_2O$ needed:
   86 ppm (mg/L) x 3.668 = 315 mg/L
4. Amount of Cl added (Table 3.2 has no factor for the conversion from calcium chloride to chlorine, so the atomic weight fraction must be used):

$$\frac{\text{Atomic weight of chlorine}}{\text{Molecular weight of calcium chloride}} \times 315\,\text{mg/L}$$

$$\frac{2(35.5)}{147} \times 315 = 152\,\text{mg/L (ppm) Cl}$$

This level of chloride is tolerable to the plants as long as the level of sodium in the raw water and other fertilizers used does not exceed 100–150 ppm.

Once the weight for each compound in the nutrient formulation has been determined for a given tank volume, changes can be easily calculated by use of ratios. These changes using ratios allow you to adjust tank volumes or concentrations for any of the elements. For example, to calculate the amount of calcium nitrate needed to provide 200 ppm Ca in a 500-US-gal tank, instead of the original 300-US-gal tank used in the example earlier, simply use the ratio:

$$\frac{500\ \text{US gal}}{300\ \text{US gal}} \times 1{,}034.4\text{g of } Ca(NO_3)_2 = 1{,}724\,\text{g of } Ca(NO_3)_2$$

or 500/300 x 2.28 lb = 3.8 lb
= 3 lb + (0.8 lb x 16 oz)
= 3 lb 12.8 oz of $Ca(NO_3)_2$

Often it is necessary to change the levels of individual elements during weather changes, plant growth stages, or the presence of deficiencies or toxicities revealed by symptoms on the plants and/or nutrient and tissue analyses. For example, to change the concentration of Ca from 200 to 175 ppm in the same tank volume (300 US gal),

$$\frac{175\ \text{ppm Ca}}{200\ \text{ppm Ca}} \times 1{,}034.4\text{g} = 905\,\text{g of calcium nitrate}$$

or

175/200 x 2.28 lb = 1.995 lb; round off to 2.0 lb

Remember, this also affects the level of the other elements in compounds containing more than one essential element. The change in the nitrogen level is:

175/200 x 140 ppm N = 122.5 ppm N

3.6.3 Calculations for Chemical Substitutions for Fertilizers

In some areas of the world a number of basic fertilizers required may not be available. In that case, it becomes necessary to substitute other chemicals that are available to provide the needed amount of essential elements. Calculations for such substitutions are as follows:

1. Substitute potassium hydroxide (KOH) and phosphoric acid (H_3PO_4) for diammonium phosphate ($(NH_4)_2HPO_4$) or monopotassium phosphate (KH_2PO_4) to supply phosphorus (P) and some potassium (K). Note that KOH must be used to neutralize the strong acid of H_3PO_4.

   The reaction is as follows:

$$H_3PO_4 + KOH \rightarrow K^+ + OH^- + 3H^+ + PO_4^{3-}$$
$$\rightarrow K^+ + PO_4^{3-} + H_2O + 2H^+$$
$$\text{Molecular weight of } H_3PO_4 = M_{H3PO4} = 97.99$$

   Need: 60 ppm of P from H_3PO_4:

$$60 \times 3.164 \text{ (from Table 3.4)} = 189.8 \text{ mg/L}$$

   The neutralization reaction is given as follows:

$$\begin{array}{ccc} 189.8 & & x \\ H_3PO_4 & + & KOH \\ 97.99 & & 56.108 \end{array}$$

   Solving for x,

$$x = \frac{189.8 \, x \; 56.108}{97.99} = 108.7 \, \text{mg/L}$$

   Hence,

$$\text{Amount of K} = \frac{39.1}{56.108} \times 108.7 = 0.6969 \times 108.7 = 75.7 \, \text{mg/L}$$

   However, phosphoric acid is a liquid; therefore, the weight required must be converted to volume measure. To do this, the specific gravity or density (D) must be used. Density is the ratio of weight to volume (D = W/V). Density of phosphoric acid is 1.834 (Appendix 4).

   Volume can be obtained by

$$D = W/V \text{ or } V = W/D, \text{ that is, } V = 189.8/1.834 = 103.5 \, \mu L/L$$

2. Substitute nitric acid (HNO_3) and calcium carbonate ($CaCO_3$) for calcium nitrate $Ca(NO_3)_2 \cdot 4 H_2O$ to supply calcium (Ca) and nitrogen (N). Note that $CaCO_3$ must be used to neutralize the strong acid of HNO_3. Add nitric acid to the calcium carbonate until all the solid just

dissolves. Dilute nitric acid may be used; it will just take more time to dissolve the calcium carbonate. The reaction is as follows:

$$CaCO_3 + 2H_2O \rightarrow Ca^{2+} + NO_3^- + H^+ + CO_3^{2-}$$
$$\rightarrow Ca^{2+} + NO_3^- + HCO_3^-$$

$CaCO_3 = M_{CaCO3} = 100.1$

Need : 150 ppm of Ca from $CaCO_3$:

$$150 \times \frac{100.1}{40.08} = 374.6\,\text{mg/L}$$

$2HNO_3 = M_{HNO3} = 63.016 \times 2 = 126.03$

The reaction is given by

$$\begin{array}{cc} 100.1 & 126.03 \\ CaCO_3 & + 2HNO_3 \\ 374.6 & x \end{array}$$

Solving for x,

$$x = \frac{374.6 \times 126.02}{100.1} = 471.6\,\text{mg/L}$$

Hence,

$$\text{Amount of N} = 471.6 \times \frac{14}{63.016} = 104\ \text{mg/L}$$

Since HNO_3 is a liquid, the amount must be converted to volume measure:

$$D = 1.5027$$

$$D = \frac{W}{V} \text{ or } V = \frac{W}{D} = \frac{471.6}{1.5027} = 313.8\,\text{uL/L}$$

Often, HNO_3 is not 100% pure; therefore, it must be adjusted for the percentage purity.
In summary, 375 mg/L of $CaCO_3$ and 314 *u*L/L of HNO_3 will provide 150 ppm Ca and 104 ppm N.

3. Substitute nitric acid (HNO_3) and potassium hydroxide (KOH) for potassium nitrate (KNO_3). Note that KOH must be used to neutralize the strong acidity of HNO_3. The reaction is as follows:

$$KOH + HNO_3 \rightarrow K^+ + NO_3^- + H_2O$$

Amount of K needed in formulation is 150 ppm. From KOH used with H_3PO_4 for P source, there is 76 ppm of K; therefore, there is still a need for 150 – 76 = 74 ppm K.

KOH:

$$74 \times \frac{56.108}{39.1} = 106\,\text{mg/L}$$

HNO_3:

$$\begin{array}{ccc} 56.108 & & 63.016 \\ \text{KOH} & + & \text{HNO}_3 \\ 106 & & \text{x} \end{array}$$

$$\text{x} = \frac{106 \times 63.016}{56.108} = 119\,\text{mg/L}$$

$$\text{Amount of N} = 119 \times \frac{14}{63.016} = 26.4\,\text{mg/L}$$

Since HNO_3 is a liquid, the amount must be converted to volume measure:

$$\text{D} = 1.5027$$

$$\text{D} = \text{W/V or V} = \text{W/D} = \frac{119.0}{1.5027} = 79.2\,u\text{L/L}$$

That is, 106 mg/L of KOH and 79.2 *u*L/L of HNO_3 will provide 74 ppm of K and 26 ppm of N.

4. To make FeEDTA chelate:
   The objective is to make a 200-kg stock solution containing 10,000 mg/L (ppm) (1% iron) of chelated iron.
   i. Dissolve 10.4 kg EDTA (acid) in a solution of 16 kg of KOH in 114 L of water. Adjust the weight of KOH used accordingly if the KOH is not 100% pure. Do not add all of the KOH to the solution initially in order to maintain the *p*H at 5.5. Should the *p*H exceed 5.5, reduce it by addition of 10% nitric acid (HNO_3) solution. If the *p*H is substantially less than 5.5, add KOH dissolved in water to the solution, slowly stirring until the *p*H reaches 5.5.
   ii. Separately dissolve 10 kg of ferrous sulfate ($FeSO_4$) in 64 L of hot water. Slowly add the ferrous sulfate solution, while stirring, to the EDTA/KOH solution of *p*H 5.5. If the *p*H goes below 5.0, add some of the KOH solution while stirring vigorously. With each addition of KOH solution, precipitation of ferrous hydroxide ($Fe(OH)_2$) will occur. As the *p*H adjusts itself, this will redissolve, but the redissolution will become slower as the *p*H of the stock solution rises closer to *p*H 5.5.
   iii. After all of the ferrous sulfate and KOH solutions have been added to the EDTA/KOH solution, weigh the final solution and adjust the volume with addition of water until a final solution weight of 200 kg is achieved.

   Example:

   To obtain 5 ppm of iron in 30,000 L of water:

   i. The stock solution contains 10,000 mg/L of iron.

ii. We need 5 mg/L (ppm) of iron in the nutrient solution.
iii. Therefore, in 30,000 L of water we need 30,000 x 5 = 150,000 mg or 150 g of iron.
iv. Hence, if the FeEDTA stock solution contains 10,000 mg/L or 10 g/L of iron, we need

For 150 g of iron: 150/10 = 15 L of FeEDTA stock solution.

Note: The density of a compound should be obtained from the manufacturer as variations will occur among sources. A general table of solubilities and densities is given in Appendix 4.

3.6.4 Nutrient Formulation Adjustments

Since the nutrient formulation will have to be adjusted frequently during the growing of any crop, it is necessary to understand the calculations and manipulations outlined in Section 3.6.3. Many claims have been made as to the derivation of "optimum formulations" for a particular crop. Too often, however, these claims are not substantiated and cannot be supported since the optimum formulation depends on too many variables, which cannot be controlled. An optimum formulation would depend on the following variables:

1. Plant species and variety.
2. Stage of plant growth.
3. Part of the plant representing the harvested crop (root, stem, leaf, fruit).
4. Season of year – day length.
5. Weather – temperature, light intensity, sunshine hours.

Different varieties and plant species have different nutrient requirements, particularly nitrogen, phosphorus, and potassium. For example, lettuce and other leafy vegetables can be given higher rates of nitrogen than tomatoes or cucumbers. The latter two require higher rates of phosphorus, potassium, and calcium than do leafy plants.

Ulises Durany (1982) states that the nitrogen (N) level should remain lower (N = 80 – 90 ppm) for species that produce fruit than those species producing leaves (N = 140 ppm). For species that are grown for roots, potassium (K) should be higher (K = 300 ppm). For lettuce, on the other hand, relatively low levels of potassium (K = 150 ppm) favor the closing of the heads and therefore result in greater weights.

The proportions among the various elements must vary according to the species of plant, the growth cycle and development of the plant, and climatic conditions, particularly light intensity and duration. When high K:N ratios of a nutrient formulation are used on tomatoes and peppers, the upper part of the plants will have shorter and smaller leaves. In some varieties of tomatoes this can cause green shoulder and sunscald and possibly make the fruit more susceptible to blossom-end rot (BER).

In peppers, reduction in leaf growth in the top of the plant will make the fruit very prone to sunscald. That is, the fruit is exposed to the direct sunlight at the top of the plant without sufficient shading from the upper leaves and results in the fruit heating up to temperatures that cause burning. Temperatures in excess of 38^0F (100^0F) have been reported in tomatoes at the top of the plant without any shading from leaves above. The developing fruit of peppers are particularly affected by high light intensity at the top of the plant. Keeping the plants in a more vegetative state to develop a large canopy will protect the fruit from direct sunlight. Automatic shading systems to reduce direct sunlight by 35–40% will assist in reducing sunscald, but still, the plants need to be vigorous at the top to overcome this effect on the fruit and subsequent loss of production.

Nutrient formulations are generally composed of several different levels to be used at the different stages of plant growth. Formulations for tomatoes, cucumbers, and peppers usually consist of three levels – A, B, and C. These levels apply mainly to the macroelements, with some small adjustments to the microelements. In the past, the three levels were somewhat simplified to formulation A being approximately one-third of C, and B being two-thirds of C. However, today with more experience with these greenhouse crops, more specific adjustments are made to the macroelements and not necessarily in this simplified ratio. These adjustments will vary with location, climate, and growing method (hydroponic system).

For tomatoes grown in greenhouses in northern temperate climates, the formulations are divided into seeding and early seedling development (phase I), planting into the growing system and early growth (phase II), and production, training, and pruning (phase III). This would be similar for peppers.

In cucumbers, formulations are partitioned into three distinct phases based on fruit development and its location. Phase I is the period from seeding until the first cucumber is developing to 4–5 in. at the seventh to eighth node or up to the tenth node, which depends on light conditions to permit the plant to grow large lower leaves. Phase II is during the production of five to six stem fruits. Phase III is after harvesting all the stem fruits and when fruit development on the laterals begins and thereafter.

Some typical nutrient formulations derived over the years by various researchers and commercial growers are given in Table 3.7.

Leafy vegetables may use a two-level formulation. The first level (about half of the final level) is used until the plants are about 3–4 wk old, and the second (full strength) level thereafter.

In general, plants harvested for their leaves can tolerate higher N levels since nitrogen promotes vegetative growth. However, plants grown for fruit production should have lower N and higher P, K, and Ca levels. Under high light conditions, plants will use more nitrogen than under poor light.

High potassium (K) levels during the fall and early winter will improve fruit quality. This potassium/nitrogen ratio (K:N) is more important and should be varied with the climate. During the longer sunny summer days, the plant needs more nitrogen and less potassium than during the shorter, darker winter days. It is common practice therefore to double the ratio of K:N during the winter. This will make for harder growth in winter than would take place on a summer formulation.

Ulises Durany (1982) recommends that for the development of tomatoes during the initial vegetative phase, the N:K proportion should be 1:5 (e.g., 80 ppm N: 400 ppm K); in the intermediate phase during blossoming and fruit-set, the N:K ratio should be 1:3 (e.g., 110 ppm N: 330 ppm K); and the mature stage with ripening fruit should have a N:K ratio of 1:1.5 (e.g., 140 ppm N: 210 ppm K). This can be achieved through the use of potassium nitrate and calcium nitrate with potassium sulfate.

Schwarz (1968) lists a number of ratios for N:P:K to be used during the summer and winter seasons for various crops grown in European, Mediterranean, and subtropical climates (Table 3.8).

3.6.5 Calculation of N:P:K Ratios

The ratios of N:P:K are based on N, P_2O_5, and K_2O. These are the figures given as guaranteed analyses on fertilizer labels. For example, 12-4-8 indicates 12% N, 4% P_2O_5, and 8% K_2O. Nutrient solutions in hydroponics are expressed in parts per million (ppm) or milligrams per liter (mg/L). To make conversions to percent: 1% = 10,000 ppm. The ratios are expressed only for the macroelements. For example, we can use a typical lettuce formulation: N = 200 ppm, P = 50 ppm, K = 250 ppm, Ca = 200 ppm, Mg = 50 ppm. These are concentrations of each of these elements.

First, convert K to K_2O and P to P_2O_5.
Using conversion factors from Table 3.2.
250 ppm of K is equivalent to 250 x 1.205 = 301 ppm of K_2O
50 ppm of P is equivalent to 50 x 2.292 = 115 ppm of P_2O_5

TABLE 3.7
Composition of Nutrient Solutions (ppm)

References	*p*H	Ca	Mg	Na	K	N as NH_4	N as NO_3^-	P as PO_4^{3-}	S as SO_4^{2-}	Cl	Fe	Mn	Cu	Zn	B	Mo
Knopp (1865)		244	24		168		206	57	32		**na					
Shive (1915)		208	484		562		148	448	640		**na					
Hoagland (1919)	6.8	200	99	12	284		158	44	125	18	**na					
Jones & Shive (1921)		292	172		102	39	204	65	227		0.8					
Rothamsted	6.2	116	48		593		139	117	157	17	8	0.25			0.2	
Hoagland & Snyder (1933, 1938)		200	48		234		210	31	64		**na	0.1	0.014	0.01	0.1	0.016
Hoagland & Arnon (1938)		160	48		234	14	196	31	64		*0.6	0.5	0.02	0.05	0.5	0.01
Long Ashton Soln	5.5-6.0	134 to 300	36	30	130 to 295		140 to 284	41	48	3.5	5.6 or 2.8	0.55	0.064	0.065	0.5	0.05
Eaton (1931)		240	72		117		168	93	96		0.8	0.5			1	
Shive & Robbins (1942)		60	53	92	117		56	46	70	107	**na	0.15		0.15	0.1	
Robbins (1946)		200	48		195		196	31	64		0.5	0.25	0.02	0.25	0.25	0.01
White (1943)	4.8	50	72	70	65		47	4	140	31	1.0	1.67	0.005	0.59	0.26	0.001
Duclos (1957)	5-6	136	72		234		210	27	32		3	0.25	0.15	0.25	0.4	2.5
Tumanov (1960)	6-7	300 to 500	50		150		100 to 150	80 – 100	64	4	2	0.5	0.05	0.1	0.5	0.02
A. J. Abbott	6.5	210	50		200		150	60	147		5.6	0.55	0.064	0.065	0.5	0.05
E. B. Kidson	5.5	340	54	35	234		208	57	114	75	2	0.25	0.05	0.05	0.5	0.1
Purdue A		200	96		390	28	70	63	607		2.0	0.3	0.02	0.05	0.5	
(1948) B		200	96		390	28	140	63	447		1.0	0.3	0.02	0.05	0.5	
C		120	96		390	14	224	63	64		1.0	0.3	0.02	0.05	0.5	
Schwartz (Israel)		124	43		312		**98	93	160							
Schwartz (California)		160	48		234	15	196	31	64							
Schwartz (New Jersey)		180	55		90	20	126	71	96							
Schwartz (South Africa)		320	50		300		200	65								
CDA A		131	22		209	33	93	36.7	29.5	188	1.7	0.8	0.035	0.094	0.46	0.027
Saanichton B		146	22		209	33	135	36.7	29.5	108	1.7	0.8	0.035	0.094	0.46	0.027
B.C. Canada C		146	22		209	33	177	36.7	29.5		1.7	0.8	0.035	0.094	0.46	0.027
Dr. Pilgrim C		272	54		400		143.4	93	237.5							

Elizabeth	B	204	41		300		107.6	70	178							
N.C., USA	A	136	27		200		71.7	46.5	119							
Dr. H.M. Resh	C	197	44		400	30	145	65	197.5		2	0.5	0.03	0.05	0.5	0.02
Univ. of B.C	B	148	33		300	20	110	55	144.3		2	0.5	0.03	0.05	0.5	0.02
Vancouver	A	98	22		200	10	80	40	83.2		2	0.5	0.03	0.05	0.5	0.02
Canada (1971)																
Dr. H.M. Resh	Tropical – Dry	250	36		200	53	177	60	129		5	0.5	0.03	0.05	0.5	0.02
	Tropical – Wet	150	50		150	32	115	50	52		5	0.5	0.03	0.05	0.5	0.02
Dr. H.M. Resh	Lettuce	200	40		210	25	165	50	113		5	0.5	0.1	0.1	0.5	0.05
Florida (1989)	Calif. (1993)															
Dr. H.M. Resh	Cucumbers I	100	20		175	3	128	27	26		2	0.8	0.07	0.1	0.3	0.03
Florida	II	220	40		350	7	267	55	53		3	0.8	0.07	0.1	0.3	0.03
(1990)	III	200	45		400	7	255	55	82		2	0.8	0.1	0.33	0.4	0.05
Dr. H.M. Resh	Lettuce	200	50	#50	210		185 to	50	66	#65 to	5	0.5	0.15	0.15	0.3	0.05
Anguilla, B.W.I. (2010)				to 90			195			253						
Dr. H.M. Resh	Tomato A	240	50		201		169	49	119		2.5	0.58	0.15	0.4	0.3	0.03
Anguilla, B.W.I.	B	200	60		351		137	49	196		2.5	0.58	0.15	0.4	0.3	0.03
(2010)	C	214	50		379		177	49	145		2.5	0.58 to 0.6	0.15	0.3	0.3	0.05
Sonneveld & Straver	Tomato I	240	48		195	7	224	46.5	64		2.3	0.6	0.05	0.4	0.3	0.05
Netherlands	II	190	60		351		189	46.5	128		2.3	0.6	0.05	0.7	0.3	0.05
(1992)	III	170	48		341	18	192	38.7	120		2.3	0.6	0.05	0.3	0.3	0.05
Sonneveld & Straver	Cucumber I	185	33		270	18	190	39	90		2.3	0.6	0.05	0.4	0.4	0.05
Netherlands	II	210	33		345	18	246	39	65		2.3	0.6	0.05	0.4	0.4	0.05
(1992)	III	170	36		293	18	213	39	44		2.3	0.6	0.05	0.4	0.3	0.05

* Add three times weekly.

** na, information not available or indicated trace or as required

These were sodium and chloride levels in the raw water from sea water desalinated by reverse osmosis. These level variations were present in all formulations used in Anguilla, for lettuce, herbs, tomatoes, cucumbers, and peppers for the period 1999 through 2016.

TABLE 3.8
Ratios of N:P:K Recommended for Summer and Winter Seasons in Several Climatic Regions

Crop, Climate, Season		N	P	K
	Tomato (mature stage)			
Middle European climate	Summer	1	0.2–0.3	1.0–1.5
	Winter	1	0.3–0.5	2–4
Mediterranean and	Summer	1	0.2	1
subtropical climate	Winter	1	0.3	1.5–2.0
	Lettuce and other leafy vegetables			
	Summer	1	0.2	1
	Winter	2	0.3	2
	Ammonium:nitrate ratio (NH_4:NO_3)			
	Summer	1:3–4		
	Winter	1:4–8		

Source: Modified from Schwarz, M., *Guide to Commercial Hydroponics*, Israel University Press, Jerusalem, 1968, p.32.

To find the ratios it is not necessary to convert to percent, simply use the ppm levels.
Using N as the denominator, that is, 200 ppm, then the ratios are as follows:

Calculations: N: 200/200 = 1.0, P: 115/200 = 0.58, K: 301/200 = 1.5
N:P:K Ratio is: 1.0 – 0.58 – 1.5

To make ratios into whole numbers simply multiply all the numbers by a common factor that gets them close to whole numbers.

Multiply by 2: N:P:K is 2.0 – 1.16 – 3.0
Multiply by 4: N:P:K is 4.0 – 2.3 – 6.0

The N:P:K ratio multiplied by 4 is most convenient to use. The next step is to include Ca and Mg ratios relative to the N:P:K ratio. The above example is then adjusted to include Ca and Mg using N of 200 ppm as the denominator.

Ca: 200/200 = 1.0, Mg: 50/200 = 0.25
N:Ca:Mg is: 1.0 – 1.0 – 0.25
Multiply by 4: 4 – 4 – 1
Then, N:P:K:Ca:Mg is: 4 – 2.3 – 6 – 4 – 1

The Ca:Mg ratio is important by itself to avoid high Mg levels that may antagonize Ca uptake. The Ca:Mg ratio here is 4:1 based on using the N level of 200 ppm as the denominator. It happened that the N and Ca levels were the same, however, if they were different the level of Ca could be used as the denominator in determining the Ca:Mg ratio by itself. For example, if the Ca was 150 ppm and the Mg was 50 ppm then the ratios would be:

Ca: 150/150 = 1.0, Mg: 50/150 = 0.33
To express as whole numbers multiply by 3: Ca:Mg is: 3 – 1

As discussed earlier and in Table 3.8 these ratios are important in making adjustments to the nutrient solution under seasonal differences, stages of plant growth, and vegetative vs. generative phases.

3.6.6 Conversion of Dilution Rates of Soluble Fertilizer Blends to ppm of Solution

At times it may be necessary to use fertilizer blends, especially on a small scale when you do not want to store bags of basic fertilizer compounds. In that case, you must follow label rates as to the weight of the fertilizer to dissolve in a given volume of water. However, as these blends will just give you percentages of N, P_2O_5, K_2O, and any others such as Mg, Ca, and micronutrients you should convert the percentages to concentrations of each element in ppm or mg/L. For example, to convert using General Hydroponics MaxiGro 10-5-14 with 6% Ca, 2% Mg, 3% S, 0.12% Fe, and 0.05% Mn.

It also has Cu, Zn, and B, but no percentages are given on the label, only that it is on the list of compounds making up the product.

The recommended rate is 5–10 g/L of water. In the following calculations 5 g/L of water is used to demonstrate the conversion calculations.

N: 10% or 10/100 x 5 g = 0.5 g of N in the 5 g of concentrate powder.
0.5 g/L = 500 mg/L or 500 ppm

This level of nitrogen is far too high for most crops in a hydroponic system.

P_2O_5: 5% It must first be converted to P using the factor in Table 3.2 of 0.436.
5% x 0.436 = 2.18% of P
2.18% or 0.0218 x 5 g = 0.109 g of P in the 5 g of powder.
0.109 g/L = 109 mg/L or 109 ppm

This level is also high as normally for most crops 50 ppm of P is adequate.

K_2O: 14% Convert to K: 14% x 0.830 = 11.6% of K
11.6% or 0.116 x 5 g = 0.58 g of K in the 5 g of powder.
0.58 g/L = 580 mg/L or 580 ppm

This level of K is also high for most hydroponic crops that require about 400 ppm K.

Ca: 6% No conversion needed here as expressed as elemental Ca
6% or 0.06 x 5 g = 0.3 g of Ca in the 5 g of powder.
0.3 g/L = 300 mg/L or 300 ppm

This level is also high. Many hydroponic formulations call for 200 ppm of Ca.

Mg: 2% No conversion needed as it is presented as elemental Mg. Some labels may give Mg as a percent of MgO, then it must be converted to Mg.
2% or 0.02 x 5 g = 0.1 g of Mg in the 5 g of powder.
0.1 g/L = 100 mg/L or 100 ppm

This level is high as most hydroponic formulations call for about 50 ppm of Mg.

S: 3% No conversion needed.

3% or 0.03 x 5 g = 0.15 g of S in the 5 g of powder.
0.15 g/L = 150 mg/L or 150 ppm

This level is okay as plants tolerate a fairly wide range of S. Most levels are determined by the fertilizer compound weights making up the solution formulation.

Fe: 0.12% No conversion needed as label states as Fe in a chelated form.
0.12% or 0.0012 x 5 g = 0.006 g of Fe in the 5 g of powder.
0.006 g/L = 6 mg/L or 6 ppm

This level is a little high, as most formulation call for about 3 ppm of Fe.

Mn: 0.05% This is given as elemental Mn in a chelated form.
0.05% or 0.0005 x 5 g = 0.0025 g of Mn in the 5 g of powder.
0.0025 gm/L = 2.5 mg/L or 2.5 ppm

This level is high as most formulations recommend from 0.5–1.5 ppm of Mn. Lettuce usually uses the higher rate.

MaxiGro 10-5-14 does not specify the levels of the other microelements, so no calculations can be made as to their exact levels.

Overall, this product has the essential nutrients in good proportions. If the dilution rate was cut in half to 2.5 g in 1 L of water, it would be fairly optimum for a hydroponic nutrient solution. At 2.5 g/L the levels would be as follows:

N: 500 x 2.5/5 = 500 ppm x 0.5 = 250 ppm
P: 109 x 0.5 = 54.5 ppm
K: 580 x 0.5 = 290 ppm (may be low for fruiting crops at various stages)
Ca: 300 x 0.5 = 150 ppm (may be low for fruiting crops)
Mg: 100 x 0.5 = 50 ppm
S: 150 x 0.5 = 75 ppm (to correct the low K add K_2SO_4, which also increases S).
Fe: 6 x 0.5 = 3 ppm
Mn: 2.5 x 0.5 = 1.25 ppm

To verify the above calculations calculate the N:P:K:Ca:Mg ratios from the formulation above to determine that they are as indicated on the package label:

Convert P to P_2O_5: 54.5 x 2.292 = 125 ppm
Convert K to K_2O: 290 x 1.205 = 350 ppm

Using N of 250 ppm as the denominator:

N: 250/250 = 1.0 P_2O_5: 125/250 = 0.5 K_2O: 350/250 = 1.4
Ca: 150/250 = 0.6 Mg: 50/250 = 0.2

Multiply all by a factor of 10 to get to package label:

N: 10, P_2O_5: 5, K_2O: 14, Ca: 6, Mg: 2

That is: 10-5-14, 6% Ca, 2% Mg as appears on the package label.

In summary, the concentration of individual elements in a nutrient solution can be calculated from the package label N-P-K ratios given in percentages and vice versa the N-P-K ratios can be calculated from the nutrient formulation given in ppm or mg/L.

3.7 NUTRIENT STOCK SOLUTIONS

3.7.1 Injector or Proportioner System

Fertilizer injection systems have become very popular with commercial growers since they save time by reducing the number of nutrient solution preparations. They also work well in the automation of nutrient solution adjustment using computer monitoring and injection of stock solutions. Therefore, more accurate, stabilized solutions can be maintained. Injector systems are used with both open and recirculating hydroponic designs. With solution and tissue analyses, appropriate adjustments in the formulation can be made by altering the settings on the injector heads.

A fertilizer injector or proportioner automatically makes up the nutrient solution by injecting preset amounts of concentrated stock solutions into the irrigation lines. In an "open" hydroponic system (nutrient solution is not recycled) a new nutrient solution is prepared automatically with each watering cycle (Figure 3.1). Changing of the nutrient solution is eliminated. Additional stock solutions are simply made up every week or so.

In earlier designs of adding stock solutions A and B to the irrigation system, a three-way valve was used to alternate the flow of stock solution A and stock solution B during irrigation cycles. Acid was added to the stock solution A as needed to adjust the *p*H. If nitric acid was used, it could be divided over both stock solutions, whereas phosphoric acid had to remain in the stock solution B. It is important that parts made of plastic are used, to prevent corrosion by the stock solutions and entrance into the nutrient solution of elements such as copper and zinc, which could result in toxic levels to the plants.

At present, most systems use a blending or mixing tank in which the irrigation water and fertilizers are mixed homogeneously. The blending tank may be part of a water "loop" piping of large diameter (4-in. diameter or more) (10 cm) or small pumps that inject the stock solutions into a mixing tank, from where it is pumped with another pump to the irrigation system. With the "loop" piping design the different stock solutions entering the main pipe should be installed at different angles so that as they flow into the irrigation water they will not immediately come into contact with each other to prevent precipitation of the fertilizers within the main irrigation pipe. The *p*H is adjusted in the mixing tank with an acid or base as needed. The electrical conductivity (EC) and *p*H are monitored and controlled by computer at the mixing tank, and additional EC and *p*H units are installed downstream in the main irrigation line to monitor the solution and signal an alarm if preset levels are exceeded or not reached. If the alarm is set by an excess of nutrients in the mixing tank, the injection

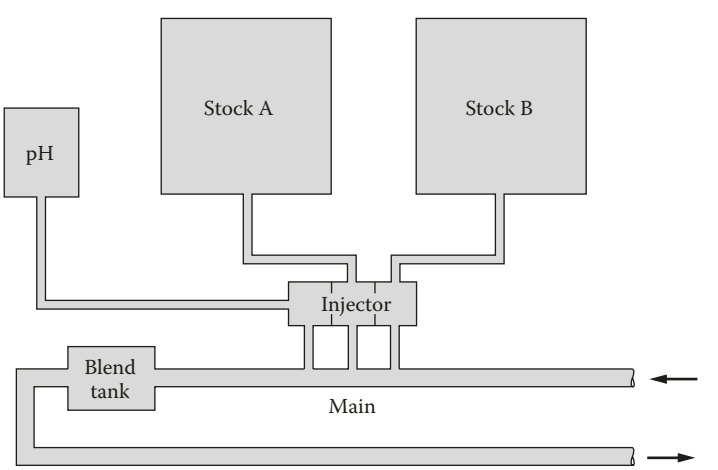

FIGURE 3.1 Layout of a basic injector system. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

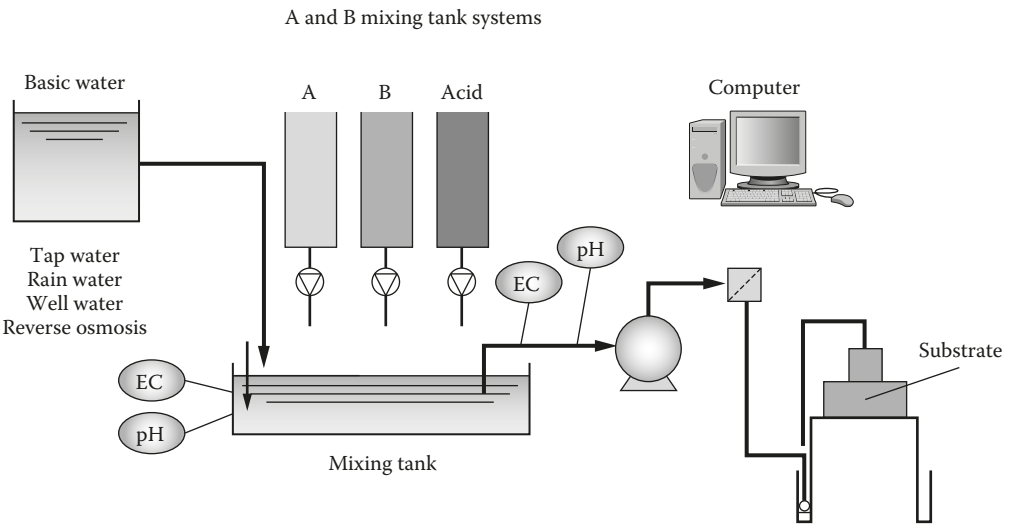

FIGURE 3.2 A, B, and acid stock mixing tank system. (Adapted from K. Welleman, The Netherlands. *6th Curso Y Congreso Internacional de Hidroponia en Mexico.* Toluca, Mexico, April 17–19, 2008b. With permission. Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

system will automatically stop until corrected in order to protect toxicity to the crop. Figure 3.2 shows A, B, and acid stock solutions with a mixing tank.

Injectors may also be used with recycle systems to automatically adjust the returning nutrient solution. Analysis of the returning solution indicates the modifications to be made to the stock solution to bring the nutrients to optimum levels before once again irrigating the plants. While nutrient solution analysis must be done by a laboratory to determine the levels of all essential elements, the general total salt levels can be determined by an EC meter. The EC meter and a *p*H meter act as sensors for the computer in monitoring the current status of the returning and outgoing solutions. The computer can then activate the injector to adjust the nutrient solution according to preset levels stored in the computer (Figure 3.3). The formulations of the nutrient stock solutions and the settings of the injector heads allow the operator to make changes in the outgoing nutrient solution to achieve optimum nutrient levels of each ion.

Some commercial growers are now taking the injection system to another level by using individual stock tanks for each fertilizer providing macroelements, trace elements, and pH adjustment. These are then dispensed individually into the mixing tank. This has a great advantage for closed hydroponic systems in that it enables the grower to selectively add given portions of each of the fertilizers and therefore make finer adjustments, almost on an individual element basis.

The returning solution can be analyzed, and additions of the individual compounds can be made at different rates according to those elements being depleted in the nutrient solution. This can be computer activated, similar to the previous system using only two stock solutions. Such a multi-injection fertilizer system is shown in Figure 3.4.

There are a number of different manufacturers of injectors (Appendix 5). The choice of a particular make will depend on the volume of nutrient solution to be injected at any given time in gallons per minute (gpm), the accuracy required for the system, the type of computer controller system, and the ability to expand the system. Some of the better makes of injectors allow addition of injector heads to expand the hydroponic system, making it unnecessary to purchase a new injector.

For example, a 3-acre (1.2-ha) hydroponic herb operation used an Anderson injector with five heads as shown in Figure 3.5. The system consisted of a 3-in. (7.6-cm)-diameter water main forming

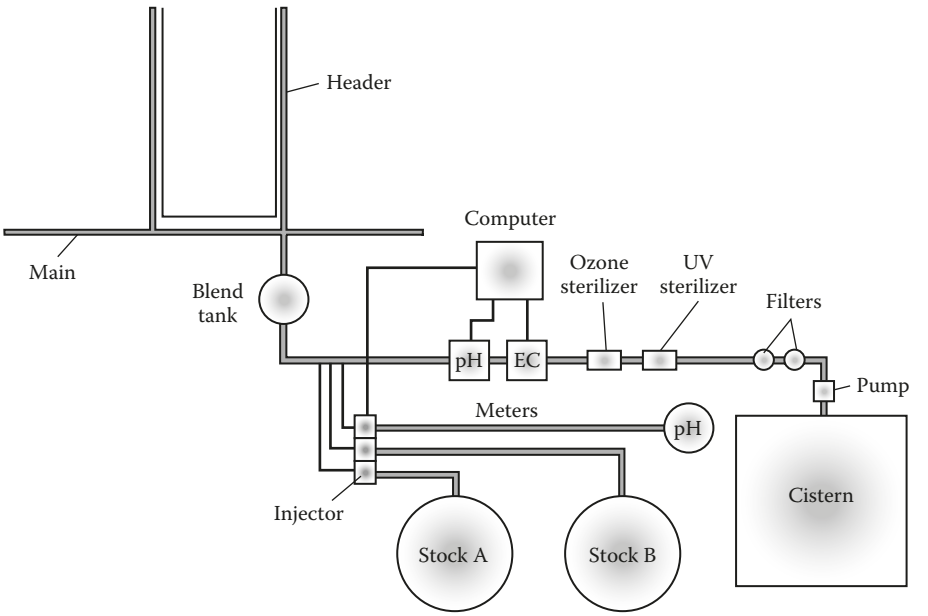

FIGURE 3.3 Layout of injector system for recirculating systems. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

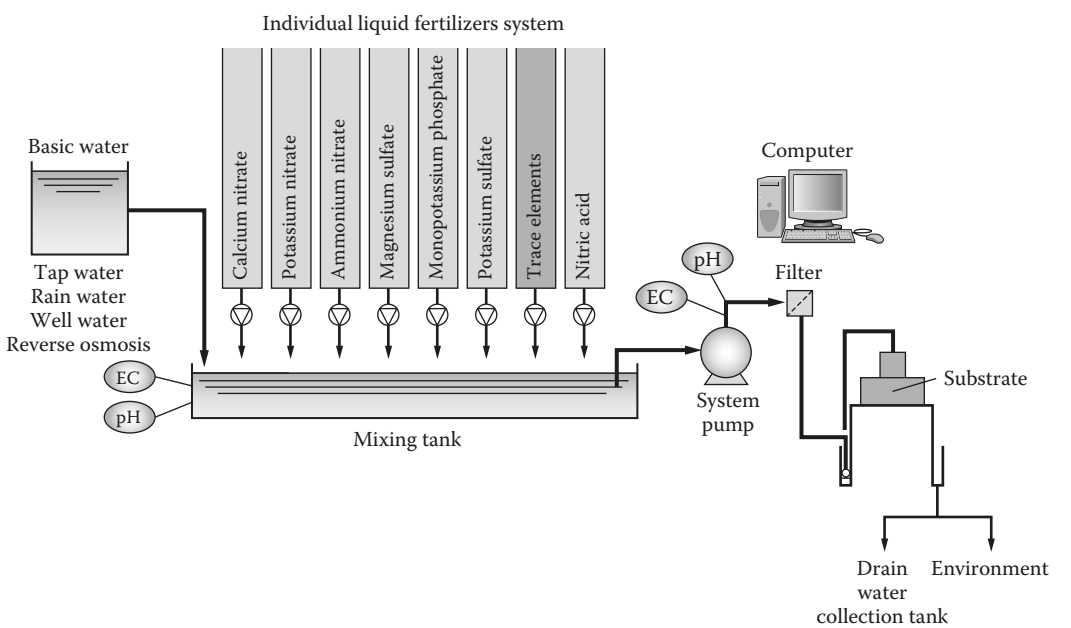

FIGURE 3.4 Individual stock mixing tank system. (Adapted from K. Welleman, The Netherlands. *6th Curso Y Congreso Internacional de Hidroponia en Mexico.* Toluca, Mexico, April 17–19, 2008b. With permission. Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 3.5 Anderson injector with five heads (on the left), paddle-wheel sensor on main line (grey area on pipe before inlet lines from injector). Water flows from back to front. (From California Watercress, Inc. Fillmore, CA. With permission.)

a loop with the injector, a blending tank, and a filter before going into the irrigation system of the hydroponic beds. The water flows from right to left in the system illustrated in Figure 3.6.

A paddle-wheel sensor upstream from the injector (Figure 3.5) monitors the flow of water. For every 4 gal (15 L) of water that passes, the sensor sends impulses to the controller (the grey box on the white panel in Figure 3.6).

The controller activates one stroke of the injector for every 4 gal (15 L) of water going through the main loop. A stroke occurs when the controller sends an electric current to the solenoid valve on the injector, opening the valve and allowing the pressure of the raw water to drive the diaphragms of the injector heads. The raw water passes through a 200-micron household filter before entering the solenoid to prevent any silt from damaging the valve. As the pressurized water (minimum of 15-20 psi or 103.5-138 kPa) enters the back of the diaphragm of each head, it pushes the diaphragm forward causing the displacement of the stock solution in front of it. The stock solution flows to the main loop via tubing and a header. Backflow preventer valves on heads of the injector and on the inlets to the stock solution header on the main loop prevent dilution from backing up on the return stroke of the diaphragms (Figure 3.5). This injector has five heads: two for stock A, two for stock B, and a smaller acid head (on the left of Figure 3.5).

Each stroke of the injector displaces 40 mL of stock solution per head at the "10" setting on the head dial. At optimum injector operation of 32 strokes per minute, the maximum flow through the system is 32 x 4 gal = 128 gal/min (484.5 L/min). The ratio of fertilizer stock to water achieved per head is 40 mL: 15,142 mL (4 US gal), or 1:378. For two heads the ratio is 80 mL: 15,142 mL, or 1:189. To obtain a 1:200 dilution, set the dial on each head of stocks A and B to 9.5. This setting gives: 9.5/10 x 40 mL = 38 mL of 200x concentration stock solution. The ratio for the two heads of each stock solution is 76 mL: 15, 142 mL, or 1:200 (fertilizer to water).

For a larger system, the impulse setting from the paddle-wheel sensor is increased at the controller. For example, if the setting is increased to one stroke per 5 gal (19 L), optimum operation would allow a flow of 5 gal x 32 strokes/min = 160 gal/min (606 L/min). However, if a 1:200 proportion was still required, an additional injector head would have to be installed. Each head is only

FIGURE 3.6 Stock tanks A and B. A 30-gal acid tank next to the upright blending tank on left, injector, and main line loop. (From California Watercress, Inc., Fillmore, CA. With permission.)

capable of displacing 40 mL of stock solution per stroke. The maximum dilution of a two-head injector on a 5gal/stroke basis is 80 mL:18,927 mL (5 US gal), or 1:236.

Alternatively, the strength of the stock solutions could be increased above 236 times. Following these principles, the injector system can be expanded with additional heads to operate with higher volumes of water flow.

The entrance of stock solutions A and B into the main loop is separated by at least 18 in. (46 cm) so that adequate mixing with raw water occurs before they come into contact with each other. Another method to ensure that no precipitation occurs is to have the entrances of the separate stock solutions into the main loop positioned at different angles to each other. That is, the two entrances should not be in line with each other; one of them should be rotated about 90 degrees from the other. As the water nutrient passes downstream, it is mixed further in an 80-gal (303-L) blending tank as shown in Figure 3.6. The acid enters the main loop several feet (60 cm) downstream from the stock solutions (small black tubing entering underneath the main loop in Figure 3.5).

The stock solutions and acid enter the injector heads with flexible tubing (Figure 3.5) from the header lines connected to the 1,500-gal (5,678-L) stock tanks A and B and a 30-gal (114-L) acid tank (Figure 3.6). The main loop carries the mixed solution from the blending tank to the hydroponic growing system (Figure 3.6). A 200-mesh filter installed downstream removes any particulate matter before the solution enters the drip irrigation system.

3.7.2 Stock Solutions

Stock solutions are concentrated nutrient solutions. Depending on the ability of the injector, the stock solutions may be prepared as 50, 100, or 200 times normal strength. A second factor that may limit the degree of concentration of the stock solution is fertilizer solubility. The least soluble fertilizer will be the limiting factor for the entire stock solution. When determining the strength of the stock solution, refer to the information on "Physical Constants of Inorganic Compounds" listed in Appendix 4.

Two separate stock solutions plus an acid solution must be prepared in individual tanks. These are generally called "stock A," "stock B," and "acid." The reason for separate solutions is that

precipitation will occur among the sulfates and nitrates of some compounds if mixed together at high concentrations. For example, the sulfates of potassium sulfate or magnesium sulfate will precipitate with calcium from calcium nitrate.

Stock A may contain half of the total potassium nitrate requirement and all of calcium nitrate, ammonium nitrate, nitric acid (to lower the *p*H of the stock solution to under 5.0), and iron chelate requirement. Stock B would consist of the other half of potassium nitrate, all of potassium sulfate, monopotassium phosphate, phosphoric acid, magnesium sulfate, and the remaining micronutrients apart from iron. Acid stock solution is diluted to about 15–20% of the concentrated liquid form available from suppliers. Care should always be exercised with such strong acids as they cause severe injury to humans. Always add acid to water, never water to acid.

Some of the acids used are nitric acid (HNO_3) (42%) (produces harmful vapors and burns the skin), sulfuric acid (H_2SO_4) (66%) (burns the skin and produces holes in clothing), phosphoric acid (H_3PO_4) (75%), and hydrochloric acid (HCl) (muriatic acid). With these strong acids, protective plastic/rubber gloves, apron, goggles, and an approved respirator should be worn. Particular care must be taken with nitric acid as it gives off toxic fumes when it comes in contact with the air.

To determine the upper limit of concentration for a stock solution, use the solubility products listed in Appendix 4. Solubility is given as the amount of grams of a specific fertilizer that may be dissolved in 100 mL of cold or hot water. Since the stock solution probably will not be heated, the values for cold water should be used. The following example demonstrates the use of these solubility factors.

Stock A:

Compound	Solubility (g/100 mL cold water)
potassium nitrate*	13.3
calcium nitrate	121.2
ammonium nitrate	118.3
nitric acid	no limit
iron chelate	very soluble

Stock B:

Compound	Solubility (g/100 mL cold water)
potassium nitrate	13.3
potassium sulfate*	12.0
monopotassium phosphate (potassium dihydrogen phosphate)	33.0
phosphoric acid	548
magnesium sulfate	71

*These are the least soluble compounds and possibly the limiting ones, depending on the weights of each required. Although micronutrients will be included in stock solution B, they have not been included in this list of solubilities since they will be required in very small amounts, which will not exceed their solubilities at the 200x concentration.

To demonstrate the calculations of a stock solution, the following nutrient formulation will be used:

N: 200 ppm	P: 50 ppm	K: 300 ppm
Ca: 200 ppm	Mg: 40 ppm	Fe: 5 ppm
Mn: 0.8 ppm	Cu: 0.07 ppm	Zn: 0.1 ppm
B: 0.3 ppm	Mo: 0.03 ppm	

Assume that raw water contains 30 ppm of Ca and 20 ppm of Mg. The following are then the adjustments to the formulation:

1. The amount of Ca to be added will be 170 ppm (200 – 30).
2. The amount of Mg to add is 20 ppm (40 – 20).

Using 1,200 US-gal tanks to store each stock solution and a 200x concentration of solution, the procedure is as follows:

1. Determine the amount of each compound to satisfy the macronutrients and adjust for impurities.

   Ca: 170 ppm (mg/L)
   i. Weight of $Ca(NO_3)_2$ (use Table 3.2 conversion factors):
   170 x 4.094 = 696 mg/L
   ii. Adjust for impurity from Table 3.3 (90% pure):

$$\frac{100}{90} \times 696\,\text{mg/L} = 773\,\text{mg/L}$$

2. Calculate the amount of the compound for the stock solution concentration (200x in this case).
   200 x 773 mg/L = 154,600 mg/L or: 154.6 g/L (1000 mg = 1 g)
3. Compare this amount with the solubility given in g/100 mL of cold water.
   i. Convert to grams per 100 mL:
   154.6 g/L
   That is, 154.6 g/1000mL (since 1 L =1000 mL) or 15.46 g/100 mL (divide by 10 to get 100 mL)
   ii. Compare with the solubility:
   15.46 g/100 mL versus 121.2 g/100 mL
   Therefore, this amount is well within the solubility limits of calcium nitrate.
4. Continue with the calculations for all macronutrient compounds.

   N: We require a total of 200 ppm from all sources. Assume that we wish to use some ammonium nitrate to supply 10 ppm of N from NH_4.
   i. Amount of N in $Ca(NO_3)_2$ added:
   696 mg/L of $Ca(NO_3)_2$ (before adjustment for purity)
   696 mg/L x 0.171 (Table 3.2 factor) = 119 mg/L (ppm)
   ii. Balance needed from sources other than calcium nitrate:
   200 – 119 = 81 ppm (mg/L)
   iii. Amount of NH_4NO_3 needed to obtain 10 ppm of N from NH_4 and 10 ppm of N from NO_3 (i.e., a total of 20 ppm N from NH_4NO_3 source):
   20 mg/L x 2.857 (Table 3.2 factor) = 57 mg/L
   iv. Adjust for purity (Table 3.3 – 98%):

$$\frac{100}{98} \times 57\,\text{mg/L} = 58\,\text{mg/L}$$

   v. For 200x concentration:
   200 x 58 mg/L = 11,600 mg/L or: 11.6 g/L

vi. Express in grams per 100 mL and compare with solubility:
11.6 g/L = 1.16 g/100 mL (divide by 10 as 1 L = 1000 mL)
1.16 g/100 mL versus 118.3 g/100 mL

Therefore, the level of ammonium nitrate is within the solubility range.

vii. Balance of N required from sources other than calcium nitrate and ammonium nitrate:
200 – (119 + 20) = 61 ppm (mg/L)

viii. Final source of N is from KNO_3:
61 mg/L x 7.221 (Table 3.2 factor) = 440.5 mg/L

ix. Adjust for purity (Table 3.3 – 95%):

$$\frac{100}{95} \times 440.5\,\text{mg/L} = 464\,\text{mg/L}$$

x. For 200x concentration:
200 x 464 mg/L = 92,800 mg/L or: 92.8 g/L

xi. Express in g/100 mL and compare to solubility:
92.8 g/L = 9.28 g/100 mL
9.28 g/100 mL versus 13.3 g/100 mL

This is within the solubility limit. Note that half of the potassium nitrate is added to stock A and the other half to stock B.

Therefore, actually 9.28/2 = 4.64 g/100 mL concentration is added to each tank. Often, a higher level of potassium nitrate is used, and therefore, splitting it between the two stock solutions keeps within the solubility limit.

K: 300 ppm (mg/L)

i. Amount of K in KNO_3 used:
440.5 mg/L x 0.387 (Table 3.2 factor) = 170.5 mg/L

ii. Balance of K needed: 300 – 170 = 130 mg/L

iii. Other sources: KH_2PO_4 and K_2SO_4
First calculate the amount of KH_2PO_4 to use to get 50 ppm of P.

P: 50 ppm (mg/L) from KH_2PO_4

i. 50 mg/L x 4.394 (Table 3.2 factor) = 220 mg/L

ii. Adjust for purity (Table 3.3 – 98%)

$$\frac{100}{98} \times 220\,\text{mg/L} = 224\,\text{mg/L}$$

iii. For 200x concentration:
200 x 224 mg/1,000 mg = 44.8 g/L or: 4.5 g/100 mL

iv. Compare with solubility:
4.5 g/100 mL vs. 33.0 g/100 mL

This is well below the solubility limit.
Now go back and calculate the K requirement from other sources (see (iii) in **K:** 300 ppm (mg/L)).

K: 300 ppm (mg/L)

v. Amount of K in 220 mg/L of KH_2PO_4

220 mg/L x 0.287 (Table 3.2 factor) = 63 ppm

vi. Balance of K needed: 300 – (170 + 63) = 67 ppm (mg/L)

vii. Amount of K_2SO_4:
67 mg/L x 2.229 = 149 mg/L

viii. Adjust for purity (90%):

$$\frac{100}{90} \times 149\,\text{mg/L} = 166\,\text{mg/L}$$

ix. For 200x concentration:
200 x 166 mg/1,000 mg = 33.2 g/L or: 3.32 g/100 mL

x. Compare with solubility:
3.32 g/100 mL vs. 12.0 g/100 mL

This level is within the solubility range.

Mg: 20 ppm (mg/L)

i. Amount of $MgSO_4$ required:
20 mg/L x 10.14 = 203 mg/L

ii. Adjust for purity (98%):

$$\frac{100}{98} \times 203\,\text{mg/L} = 207\,\text{mg/L}$$

iii. For 200x concentration:
200 x 207 mg/1,000 mg = 41.4 g/L or: 4.14 g/100 mL

iv. Compare with solubility:
4.14 g/100 mL vs. 71 g/100 mL

This level is soluble.

5. Convert all compound weights to amounts for 1,200-US-gal stock tanks.
   A. Convert 1,200 US gal to liters:
   1,200 x 3.785 = 4,542 L
   B. Calculate the weights of each compound for this volume.
      i. $Ca(NO_3)_2$: 154.6 g/L
      154.6 x 4,542 = 702,193 g or: 702.2 kg
      ii. NH_4NO_3: 11.6 g/L
      11.6 x 4,542 = 52,687 g or: 52.7 kg
      iii. KNO_3: 92.8 g/L
      92.8 x 4,542 = 421,498 g or: 421.5 kg
      That is, 421.5 kg x 2.2 lb = 927 lb
      Note that this total of 927 lb will be divided into two equal portions, one in each stock tank. Therefore, 927/2 = 463.5 lb should be added to each of stock A and B tanks.
      iv. KH_2PO_4: 44.8 g/L
      44.8 x 4,542 = 203,482 g or: 203.5 kg
      That is; 203.5 kg x 2.2 lb = 448 lb

v. K_2SO_4: 33.2 g/L
33.2 x 4,542 = 150,794 g or: 150.8 kg
That is, 150.8 kg x 2.2 lb = 332 lb
vi. $MgSO_4$: 41.4 g/L
41.4 x 4,542 = 188,039 g or: 188 kg
That is, 188 kg x 2.2 lb = 414 lb

6. Now calculate the weights for each of the micronutrient compounds.

Fe: 5 ppm (mg/L)
i. Source: FeEDTA (10%)
5 mg/L x 10.0 (Table 3.2 factor) = 50 mg/L
ii. For 200x concentration:
200 x 50 mg/L = 10,000 mg/L or: 10 g/L
iii. For 1,200 US gal (4,542 L):
10 x 4,542 = 45,420 g or: 45.4 kg
That is, 45.4 kg x 2.2 lb = 100 lb

Mn: 0.8 ppm (mg/L)
i. Amount of $MnSO_4$
0.8 mg/L x 4.061 (Table 3.2 factor) = 3.25 mg/L
ii. Adjust for percentage purity. The purity of compounds, especially that of micronutrients, differs with the manufacturer. The grower should obtain the precise percent purity for any given product from the fertilizer dealer. For calculation purposes, a purity of 90% will be used. Adjustments may be made after a solution analysis has been carried out for the new solution. The actual level of each element can be compared to the theoretical expected level of each.

$$\frac{100}{90} \times 3.25\,\text{mg/L} = 3.6\,\text{mg/L}$$

iii. For 200x concentration:
200 x 3.6 mg/L = 720 mg/L or: 0.72 g/L
iv. For 1,200 US gal (4,542 L):
0.72 x 4,542 = 3,270 g or: 3.27 kg
That is, 3.27 kg x 2.2 lb = 7.2 lb or: 7 lb 3 oz (1 lb = 16 oz; 0.2 x 16 = 3 oz)

Cu: 0.07 ppm (mg/L)
i. Source: $CuSO_4$
0.07 mg/L x 3.93 (Table 3.2 factor) = 0.275 mg/L
ii. Percent purity (98%):

$$\frac{100}{98} \times 0.275\,\text{mg/L} = 0.281\,\text{mg/L}$$

iii. For 200x concentration:
200 x 0.281 mg/L = 56 mg/L or: 0.056 g/L
iv. For 1,200 US gal:
0.056 x 4.542 = 254 g
Since this is less than 1 lb, it is more accurate to weigh it using a gram scale.

Zn: 0.1 ppm (mg/L)
i. Source: ZnEDTA (14% powder)
0.1 mg/L x 7.143 = 0.7143 mg/L
ii. For 200x concentration:
200 x 0.7143 mg/L = 143 mg/L or: 0.143 g/L
iii. For 1,200 US gal:
0.143 x 4,542 = 650 g or: 1.43 lb, which is 1 lb 7 oz

B: 0.3 ppm (mg/L)
i. Source: H_3BO_3
0.3 mg/L x 5.717 = 1.715 mg/L
ii. Percent purity (about 95%):

$$\frac{100}{95} \times 1.715\,\text{mg/L} = 1.805\,\text{mg/L}$$

iii. For 200x concentration:
200 x 1.805 mg/L = 361 mg/L or: 0.361 g/L
iv. For 1,200 US gal:
0.361 x 4,542 = 1,640 g or: 3.61 lb
That is, 3 lb 10 oz

Mo: 0.03 ppm (mg/L)
i. Source: ammonium molybdate
0.03 mg/L x 1.733 = 0.052 mg/L
ii. Percent purity is about 95%:

$$\frac{100}{95} \times 0.052\,\text{mg/L} = 0.055\,\text{mg/L}$$

iii. For 200x concentration:
200 x 0.055 mg/L = 11 mg/L
iv. For 1,200 US gal:
11 x 4,542 = 49,962 mg or: 50 g

7. Construct a table to summarize all of the information.

	Compound	Weight (lb)	Stock Sol. (g/100 mL)	Max. Sol. (g/100 mL)	Nutrient Sol. Elements (ppm) After Injection
STOCK A: (200x) (1,200-gal tank)	KNO_3	463.5	4.64	13.3	K – 85 N – 30.5
	$Ca(NO_3)_2$	1,545	15.46	121.2	Ca – 170 N – 119
	NH_4NO3	116	1.16	118.3	N – 20
	FeEDTA	100	–	Very sol.	Fe – 5
	*HNO_3	–	–	No limit	
STOCK B: (200x) (1,200-gal tank)	KNO_3	463.5	4.64	13.3	K – 85 N – 30.5
	K_2SO_4	332	3.32	12.0	K – 67 S – 27.4

Compound	Weight (lb)	Stock Sol. (g/100 mL)	Max. Sol. (g/100 mL)	Nutrient Sol. Elements (ppm) After Injection
KH_2PO_4	448	4.5	33.0	K – 63 P – 50
$MgSO_4$	414	4.14	71	Mg – 20 S – 26.4
*H_3PO_4	–	–	548	
$MnSO_4$	7 lb 3 oz	–	105.3	Mn – 0.8
$CuSO_4$	254 g	–	31.6	Cu – 0.07
ZnEDTA	1 lb 7 oz	–	Very sol.	Zn – 0.1
H_3BO_3	3 lb 10 oz	–	6.35	B – 0.3
NH_4 – Mo	50 g	–	43	Mo – 0.03

* These acids are added in sufficient quantity to lower the *p*H to 5.5. Phosphoric acid (H_3PO_4) may be substituted for KH_2PO_4 as a source of P. Then adjust the remaining compounds containing K, especially K_2SO_4, as no K will be obtained from H_3PO_4. Nutrient solution totals: NO_3 – N: 190 ppm; NH_4 – N: 10 ppm; P: 50 ppm; K: 300 ppm.

The raw water in this example contained 30 ppm of Ca and 20 ppm of Mg. This brings the total Ca to 200 ppm and Mg to 40 ppm in the final nutrient solution after injection.

Stock solutions require continuous agitation to prevent settling out of some of the fertilizer components. This may be accomplished in several ways. A motor having a long shaft with a propeller-type blade may be mounted above the opening of the tank as shown in Figure 3.7. The blade and shaft should be submersed to a position very close to the bottom of the tank. It is very important that the shaft and blade is of stainless steel to resist the corrosive nature of the nutrient solution.

A submersible pump may be placed at the bottom of each tank to circulate the solution. But it must be well sealed and should have either a plastic or a stainless steel impeller or stainless steel screws holding the pump components together. If there are any regular steel or galvanized screws in contact with the nutrient solution, they will be dissolved by the electrolytic nature of the solution within several weeks. This would then expose the motor to the solution, and the operator could easily receive an electric shock when working with the injection system.

An alternative to these methods is to use a circulating pump that has components resistant to corrosive solutions, such as a swimming pool circulation pump. The pump would be located outside and near each tank (one pump per tank). Plastic PVC piping of at least 1.5-in diameter would connect the pump inlet and outlets to the bottom of the stock solution tank as shown in Figure 3.8. An elbow is placed at the end of the outlet line in the tank to deflect the solution around the tank. The inlet end requires a check valve at its end near the base of the tank to keep the pump from losing prime. The pump should be anchored to a base of concrete or heavy wood support with anchor bolts to prevent it from shifting position. The pump must run continuously.

With smaller stock tanks of less than 500 gal, an air pump can be used to agitate the solution. Connect the air pump using 0.5-in.-diameter polyethylene tubing and a tee forming one line to each tank. Connect the polyethylene tubing with an adapter to a 12-in. air diffuser (air stone) available from aquatic suppliers. Position the air diffuser at the base of the tank. A plastic ball valve fit into each line will allow you to balance the airflow between tanks. When making up a new stock solution, remove the remaining solution and clean the tank with a 10% bleach solution. Use a submersible pump to clean the tanks.

The *p*H adjustment tank (either acid or strong base) does not require agitation since the contents dissolve completely in water and do not form any precipitates.

FIGURE 3.7 Stock tanks (2,300 gal.) A and B with circulation pumps. (From California Watercress, Inc., Fillmore, CA. With permission.)

To facilitate the filling of the stock tanks, install a 1-in. diameter raw water line above the tanks (Figure 3.7). At the inlet end to each tank, attach a gate valve. For large operations, stock tanks should be at least 2,300 gal or larger as shown in Figure 3.9.

When using small injector system stock tanks of less than 100 US gal (378 L), the weights of individual micronutrient compounds become very small. For example, the amount of ammonium molybdate for a 200x concentration stock solution for a 100-US-gal (378 L) stock tank would be 4.17 g. Such small weights are difficult to measure on a triple-beam balance, which is accurate to 1.0 g. Also, if a nutrient solution is prepared in a storage tank at its final plant formulation without the use of stock solutions, the quantities required for micronutrient compounds are very small and therefore difficult to weigh accurately.

In these cases, it is better to use a highly concentrated stock solution for the micronutrients and store it in an opaque container. Make up a 10- to 20-gal (38- to 75-L) quantity, but not more than you expect to use within several months, as changes may have to be made in the formulation to better suit the plants during different stages of growth. Some sedimentation may occur over this period of time, so agitate the solution with a small aerator with an air diffuser in the solution as described earlier.

To illustrate the derivation of a micronutrient stock solution, the same micronutrient formulation will be used as in the above example. That is, Mn: 0.8 ppm; Cu: 0.07 ppm; Zn: 0.1 ppm; B: 0.3 ppm;

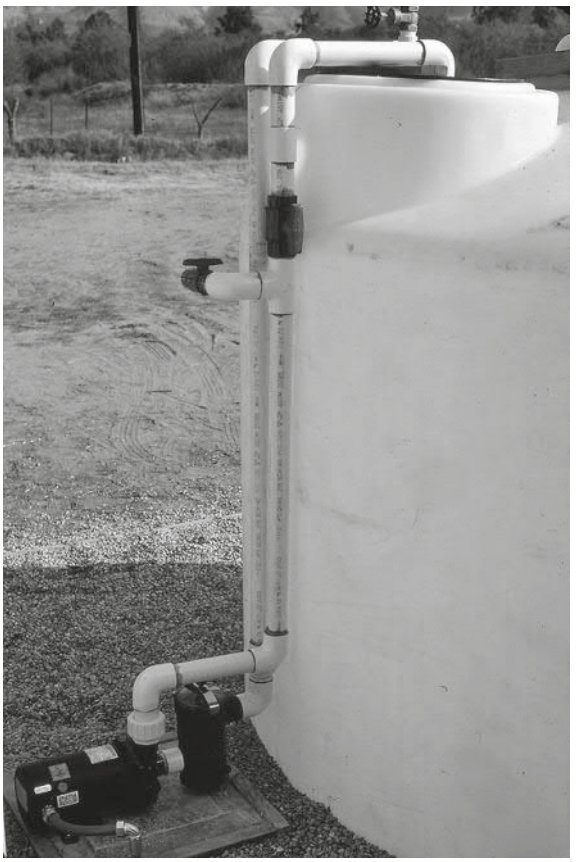

FIGURE 3.8 Circulation pump with plumbing to agitate the stock solution. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 3.9 Image of 2,300-gal stock tanks with injector shed. (From California Watercress, Inc., Fillmore, CA. With permission.)

and Mo: 0.03 ppm. Note that iron (Fe) is not included in this micronutrient stock solution as sufficient weight of iron is required such that it can be accurately measured on a balance.

The following situation will exemplify the calculations involved in determining the weights of micronutrient compounds and their comparisons to the solubilities for a concentrated stock solution. Prepare a nutrient solution at normal plant strength in a 1,000-US-gal nutrient tank (not a stock solution) and use a 600x strength micronutrient stock solution to supply the micronutrients to this tank. The three-step procedure is as follows:

Step 1. Determine the quantities of each compound needed for the 1,000-US-gal nutrient tank. At this time, only the calculations for the micronutrients will be demonstrated as those for the macronutrients are shown in Section 3.6.2.

Mn: 0.8 ppm (mg/L)

i. Amount of $MnSO_4$:
   0.8 mg/L x 4.061 (Table 3.2 factor) = 3.25 mg/L
ii. Adjust for purity (90%):

$$\frac{100}{90} \times 3.25\,\text{mg/L} = 3.6\,\text{mg/L}$$

iii. For 1,000-US-gal tank:
   1,000 x 3.785 L = 3,785 L
   3,785 x 3.6 mg/L = 13,626 mg or: 13.6 g

Cu: 0.07 ppm (mg/L)

i. Amount of $CuSO_4$:
   0.07 mg/L x 3.93 = 0.275 mg/L
ii. Adjust for purity (98%):

$$\frac{100}{98} \times 0.275\,\text{mg/L} = 0.281\,\text{mg/L}$$

iii. For 1,000-US-gal tank:
   3,785 x 0.281 mg/L = 1,064 mg or: 1.064 g

Zn: 0.1 ppm (mg/L)

i. Amount of $ZnSO_4$:
   0.1 mg/L x 4.40 = 0.44 mg/L
ii. Adjust for purity (90%):

$$\frac{100}{90} \times 0.44\,\text{mg/L} = 0.4889\ \text{mg/L}$$

iii. For 1,000-US-gal tank:
   3.785 x 0.4889 mg/L = 1,850 mg or: 1.85 g

B: 0.3 ppm (mg/L)

i. Source: H_3BO_3
   0.3 mg/L x 5.717 = 1.715 mg/L

ii. Percent purity (95%):

$$\frac{100}{95} \times 1.715\,\text{mg/L} = 1.805\,\text{mg/L}$$

iii. For 1,000-US-gal tank:
3,785 x 1.805 mg/L = 6,832 mg or: 6.83 g

Mo: 0.03 ppm (mg/L)

i. Source: ammonium molybdate
0.03 mg/L x 1.733 = 0.052 mg/L

ii. Percent purity (95%):

$$\frac{100}{95} \times 0.052\,\text{mg/L} = 0.055\,\text{mg/L}$$

iii. For 1,000-US-gal tank:
3,785 x 0.055 mg/L = 208.2 mg or: 0.208 g

It is clear from these calculations that the amounts are too small to be weighed accurately by a triple-beam balance.

Step 2. Calculate the quantities of each micronutrient compound for a 600x concentration stock solution (use a 10-U.S-gal stock tank).

Mn: For 0.8 ppm (mg/L), use 3.6 mg/L of $MnSO_4$ (as calculated in (ii) in "Mn: 0.8 ppm (mg/L)").

i. For 10-US-gal stock tank:
10 x 3.785 L = 37.85 L
37.85 x 3.6 mg/L = 136.26 mg

ii. 600x concentration:
600 x 136.26 mg = 81,756 mg or: 81.8 g

iii. Convert 81.8 g in 37.85 L to g/100 mL and compare it to the solubility limit:
81.8 g/37.85 L = 2.16 g/L or 0.216 g/100 mL
0.216 g/100 mL versus 105.3 g/100 mL

This concentration is well within the solubility range.

Cu: For 0.07 ppm (mg/L), use 0.281 mg/L of $CuSO_4$.

i. For 10-US-gal stock tank:
37.85 x 0.281 mg/L = 10.64 mg

ii. 600x concentration:
600 x 10.64 mg = 6,384 mg or: 6.4 g

iii. Convert to grams per 100 mL:

$$\frac{6.4\text{g}}{37.85\text{L}} = 0.169\,\text{g/L or: } 0.0169\,\text{g/100mL}$$

0.0169 g/100 mL versus 31.6 g/100 mL
This is within the solubility limit.

Zn: For 0.1 ppm (mg/L), use 0.4889 mg/L of $ZnSO_4$:

i. For 10-US-gal stock tank:
37.85 x 0.4889 mg/L = 18.505 mg
ii. 600x concentration:
600 x 18.505 mg = 11,103 mg or: 11.1 g
iii. Convert to grams per100 mL:

$$\frac{11.1\,\text{g}}{37.85\,\text{L}} = 0.2932\,\text{g/L} \quad \text{or}: 0.0293\,\text{g/100\,mL}$$

0.0293 g/100 mL versus 96.5 g/100 mL (from Appendix 4)

This concentration is well below the solubility limit.

B: For 0.3 ppm (mg/L), use 1.805 mg/L of H_3BO_3.

i. For 10-US-gallon stock tank:
37.85 x 1.805 mg/L = 68.32 mg
ii. 600x concentration:
600 x 68.32 mg = 40,992 mg or: 41 g
iii. Convert to grams per 100 mL:

$$\frac{41\,\text{g}}{37.85\,\text{L}} + 1.083\,\text{g/L} \text{ or: } 0.108\,\text{g/100mL}$$

0.108 g/100 mL versus 6.35 g/100 mL

This level is within the solubility range.

Mo: For 0.03 ppm (mg/L), use 0.055 mg/L of ammonium molybdate.

i. For 10-US-gal stock tank:
37.85 x 0.055 mg/L = 2.082 mg
ii. 600x concentration:
600 x 2.082 mg = 1,249 mg or: 1.249 g
iii. Convert to grams per 100 mL:

$$\frac{1.249\,\text{g}}{37.85\,\text{L}} = 0.033\,\text{g/L} \text{ or}: 0.0033\,\text{g/100mL}$$

0.0033 g/100 mL vs. 43 g/100 mL

This is well below the solubility limit.

Step 3. The final step is to calculate the volume of a 600x concentration stock solution in a 10-US-gal tank to add to a 1,000-US-gal nutrient solution to obtain 1x concentration. It must be diluted to a ratio of 1 part of stock solution to 600 parts of water, that is, 600:1. Therefore, for 1 US gal of nutrient solution, 1/600 US gal of 600x stock solution would be required. It is easiest to set up a ratio with one unknown (x) as follows:

$$\frac{1.0}{1/600} = \frac{1{,}000}{x} \quad \frac{(1 \times \text{nutrient solution})}{(600 \times \text{stock solution})}$$

x = 1,000 x 1/600 (cross multiply)
x = 1,000/600 = 1.67 US gallons

Convert to liters:

1.67 US gal x 3.785 L = 6.308 L or: 6,308 mL

In summary, 6.308 L of 600x concentration stock solution would be added to the 1,000-US-gal nutrient tank of 1x strength solution. If the nutrient solution had to be prepared once a week, the 10 US gal of 600x stock solution would last for six weeks. Create a summary table as follows:

Micronutrient Stock Solution 600x in 10-US-Gal Tank

Compound	Weight (g)	Element (ppm)
$MnSO_4$	81.8	Mn: 0.8
$CuSO_4$	6.4	Cu: 0.07
$ZnSO_4$	11.1	Zn: 0.1
H_3BO_4	41.0	B: 0.3
NH_4-Mo	1.25	Mo: 0.03

3.8 PREPARING THE NUTRIENT SOLUTION

The preparation of the nutrient solution will vary depending on the nutrient solution tank volume and whether a normal strength or a stock solution is used.

3.8.1 Preparing Normal Strength Solutions

For small-volume tanks (less than 2,000 gal), individual fertilizer compounds may be weighed in advance and placed in plastic bags. A felt pen may be used to write the compound formula on each bag to avoid any confusion in its future use. Compounds required in smaller quantities such as grams may be weighed using a triple-beam balance. The micronutrients may be placed in one bag together, with the exception of iron, which should be in a separate bag. The macronutrient compounds should be weighed using a scale capable of 20–30 lb. As mentioned earlier, any compound that is required in an amount less than 1 lb should be weighed using the gram balance. Generally, it is faster if at least five batches are weighed when making up the formulations. Do not make too many as it may be necessary to change the formulation due to plant growth or weather conditions.

With large-volume tanks, weigh only those fertilizers needed for that batch. Weigh each fertilizer salt separately, arranging them in piles on polyethylene sheets or in buckets so there is no loss. This should be done accurately to within plus or minus 5% using either a gram scale or a pound scale depending on the weights required of each.

Continue using the following procedure:

1. Fill the nutrient solution storage tank with water to about one-third full.
2. Dissolve each fertilizer salt individually in a 5-gal bucket of water. Add the water to the fertilizer and stir vigorously. Use a hose and nozzle to assist in mixing. Usually, the entire amount of fertilizer will not dissolve on the first addition of water. Pour off the dissolved liquid portion into the storage tank and repeat adding water, stirring and canting off the dissolved portion until the entire salt has entered the solution. Use hot water with salts that are hard to dissolve.
3. Dissolve the macronutrients first, then the micronutrients.

4. In small systems such as backyard greenhouses, all the sulfates can be mixed together in the dry form before dissolving, for example, K_2SO_4, $MgSO_4$. Then the nitrates and phosphates can be mixed in dry form before dissolving, for example, KNO_3, KH_2PO_4. Add $Ca(NO_3)_2$ last.
5. With larger systems, add potassium sulfate first. For better mixing, operate the irrigation pump of the nutrient solution system with the bypass valve fully open and the valve to the greenhouses closed. Keep the pump circulating the nutrient solution in the storage tank until all of the solution is prepared.
6. Fill the tank to at least half, but no more than two-thirds, and then add potassium nitrate.
7. Fill the tank to three-quarters, and then add magnesium sulfate and monopotassium phosphate.
8. Add calcium nitrate slowly, while circulating the solution.
9. Add the micronutrients with the exception of iron chelate.
10. Check the *p*H of the nutrient solution and adjust, if necessary, with either sulfuric acid (H_2SO_4) or potassium hydroxide (KOH). High *p*H (more than 7.0) causes precipitation of Fe^{2+}, Mn^{2+}, PO_4^{3-}, Ca^{2+}, and Mg^{2+} as insoluble and unavailable salts.
11. Add the iron chelate (FeEDTA) and top up the tank to the final volume.
12. Check the *p*H and adjust it between 5.8 and 6.4 depending on the crop's optimum *p*H level.
13. If a closed recirculating hydroponic system is being used, circulate the nutrient solution through the system for 5–10 min, check the *p*H again, and adjust it again if necessary.

3.8.2 Preparing Stock Solutions

When preparing stock solutions, larger weights of each compound will be required, so prepare only one batch of solution. Weigh each compound separately. Often whole sacks (50 lb or 100 lb) will be used, so only weigh the additional amount needed. For example, if 414 lb of magnesium sulfate is one component, use eight 50-lb or four 100-lb bags and then weigh out the additional 14 lb on a scale.

If 5-gal buckets are being used to dissolve the fertilizer salts, fill the bucket only to one-third capacity to allow sufficient water to dissolve the compound. By using 15–20 buckets, one person can steadily be dissolving the fertilizer while another pours off the solution into the storage tank. Another method, other than using buckets, is to have a mixing tank with a circulation pump to mix each fertilizer separately; once dissolved, pump the solution into the stock-solution storage tank as shown in Figure 3.10. When mixing, be careful not to use more water than the stock tank can hold.

When making up stock solutions, do not add a lot of water to the stock tank before beginning the mixing process, or the final volume may be exceeded in the dissolution process alone.

Add only half of the potassium nitrate to each stock tank.

For stock A, the sequence of adding the fertilizers is as follows: half of the potassium nitrate, then calcium nitrate, ammonium nitrate, and finally iron chelate after adjusting the *p*H to about 5.5. Top up the tank with water to within 10 gal of the final solution level before adjusting the *p*H and adding the iron chelate.

For stock tank B, the sequence is as follows: the other half of the potassium nitrate and then potassium sulfate. Fill the tank to three-quarters, and then continue adding magnesium sulfate and monopotassium phosphate. Adjust the *p*H to about 5.5 after topping up the tank with water to within 30 gal of the final level, then add the micronutrients. Finally, check the *p*H again and adjust it if necessary.

The acid tank C is made up last using one of the acids described earlier. Fill the acid tank to three-quarters with water before adding the acid to the water. After stirring with a plastic pipe, top up the tank slowly with water to the final level. Should you need to use a base, such as potassium

FIGURE 3.10 Mixing tanks with pumps to stock tanks. (From California Watercress, Inc., Fillmore, CA. With permission.)

hydroxide, to increase the *p*H, follow the same procedure. Be very careful with these strong acids or bases as they burn badly; wear a protective face mask and gloves when using them.

3.9 PLANT RELATIONS AND CAUSE OF NUTRIENT SOLUTION CHANGES

In a cyclic (closed) system in which the nutrient solution is drained back to the reservoir after use, the life of the nutrient solution is 2–3 wk, depending on the season of the year and the stage of plant growth. During the summer months, for mature high-yielding plants, the nutrient solution may have to be changed as often as every week. The reason for changing the solution is that plants differentially absorb the various elements. This results in short supply of some elements before others. Just how deficient they are at any point can be determined only by atomic absorption analyses of the nutrient solution. Such analyses can be done only in costly laboratory facilities. Consequently, many people are unable to carry out such analyses. The only safeguard against a nutrient disorder then is to change the solution periodically. In some cases, it is possible to add partial formulations between changes, but this is only by trial and error and can result in excess buildup of nutrient salts that are taken up by the plant at relatively low rates.

The relative uptake of the various mineral elements by the plant is affected by the following:

a. Environmental conditions: temperature, humidity, and light intensity
b. Nature of the crop
c. Stage of plant development

As a result of the differential uptake of the various elements, the composition of the nutrient solution changes constantly. Some of the elements are depleted more rapidly than others, and the concentration is increased by the plants' relatively greater absorption of water than of salts. In addition to changes in salt composition, the *p*H also changes as a result of reactions with the aggregate and the unbalanced absorption of the anions and cations from the solutions.

3.9.1 Nutrient Analysis

Before replacing mineral elements, it is necessary to determine their concentration by chemical methods of analysis in order to determine the quantities absorbed by the plant. The difference in concentration of the mineral elements from the time of first mixing the nutrient solution to that at the time of analysis tells how much of each element must be added to bring the concentration to its original level.

Besides testing the solutions for depletions, it is necessary to test for the accumulation of unused ions such as sodium, sulfate, or chloride or for the presence of excess of toxic elements as copper or zinc.

3.9.2 Plant Tissue Analysis

By conducting both plant tissue and nutrient solution analyses, we can compare and relate plant physiological upsets to imbalances of various mineral elements in the nutrient solution. It is possible to control the changes in the nutrient solution once a precise relationship is established between fluctuations in mineral elements in the plant tissue and those in the nutrient solution. Then the nutrient solution should be adjusted before visual symptoms appear in the plant tissue. This would prevent any mineral stress from occurring within the plant and thus increase yields by allowing the plant to grow under optimum mineral nutritional conditions.

An advantage of tissue analysis over nutrient analysis is that tissue analysis indicates what has been or is being absorbed from the nutrient solution by the plant, whereas nutrient analysis indicates only the relative availability of nutrients to the plant. Actual uptake of essential elements may be restricted by conditions of the medium, solution, environmental factors, or the plant itself. For instance, if the medium is not inert and reacts with the nutrient solution, ions may be retained by the particles and become unavailable to the plant. Imbalances within the nutrient solution or fluctuating *p*H levels will reduce uptake by the plants. Diseases or nematodes in the roots of plants would reduce their absorption capacity for nutrients. Environmental factors such as insufficient light, extremes in temperatures, and insufficient carbon dioxide levels will prevent plants from efficiently utilizing the available nutrients in the solution. Plant tissue analysis measures the effects of these conditions on nutrient uptake.

The use of tissue analysis in relating the nutrient status of a plant is based on the fact that normal, healthy growth is associated with specific levels of each nutrient in certain plant tissues. Since these normal levels are not the same for all tissues in any plant or for all species, it is necessary to select an indicator tissue that is representative of a definite stage of growth. Generally, a young, vigorous leaf near the growing point of the main stem of the plant is selected. It is more reliable to take samples at various stages of growth than to concentrate on a large number of samples at any one stage since the concentration of most nutrients decreases as the plants age and mature.

To accurately relate tissue analysis results to nutritional requirements of plants, considerable data must be available on optimum levels of nutrients in specific plant species and tissues to be compared. This information is available for greenhouse tomatoes, cucumbers, lettuce, and peppers (Table 3.9). The indicator tissue for tomatoes is the fifth leaf down from the growing tip of the main stem, and it includes both petiole and blade tissue. At least 10 samples should be taken of only one variety under one fertilizer treatment. The indicator tissue for cucumbers is a young leaf, without petiole, about 10 cm (4 in.) in diameter, usually the third visible leaf from the top of the main stem. A representative sample should consist of 10 uniform replicates. The leaves should be either oven dried (70^0C for 48 h) or delivered promptly in a fresh condition to a commercial laboratory. Before drying, the blades should be separated from the petioles. Analysis for NO_3-N, PO_4-P, K, Ca, and Mg are usually performed on the petioles and for minor elements on the blades.

TABLE 3.9
Range of Nutrient Levels in Tissues of Apparently Healthy Plants

Element	Tomatoes	Cucumbers	Lettuce	Peppers
N %	4.5	5.25	4.3	3.0–4.0
	4.5–5.5	5.0–6.0	3.0–6.0	
P %	0.7	0.75	1.0	0.3–0.4
	0.6–1.0	0.7–1.0	0.8–1.3	
K %	4.5	4.75	5.4	3.5–4.5
	4.0–5.5	4.5–5.5	5.0–10.8	
Ca %	1.5	3.0	1.5	1.5–2.0
	1.5–2.5	2.0–4.0	1.1–2.1	
Mg %	0.5	0.75	0.42	0.25–0.4
	0.4–0.6	0.5–1.0	0.3–0.9	
Fe (ppm)	100	125	120	200–300
	80–150	100–150	130–600	
B (ppm)	50	40	32	40–60
	35–60	35–60	25–40	
Mn (ppm)	70	70	70	80–120
	70–150	60–150	20–150	
Zn (ppm)	30	50	45	40–50
	30–45	40–80	60–120	
Cu (ppm)	5	8	14	15–20
	4–6	5–10	7–17	
Mo (ppm)	2	2	2–3	0.4
	1–3	1–3	1–4	
N/K	1.0	1.1	0.8	0.9
	0.9–1.2	1.0–1.5		

To examine the results, date of planting, stage of growth, and previous fertilizer treatment must be known. A weekly series of tests will indicate clearly the trends in any nutrient level. A combination of nutrient and tissue analysis will allow the grower to anticipate any problems before they occur and make the necessary adjustments in the nutrient solution formulation.

3.9.3 Changing of Solutions

Work by Steiner (1980) on nutrient solutions indicates that if the ratios of nutrient uptake for a certain crop under given conditions are known, ions can be applied continuously to the solution in these mutual ratios, controlled only by a conductivity meter. While generally this is true, extended use of the same nutrient solution may result in accumulation of toxic quantities of minor elements such as zinc and copper from fertilizer impurities, or from the water itself.

The useful life of a nutrient solution depends principally on the rate of accumulation of extraneous ions, which are not utilized by the plants at rapid rates. Such an accumulation results in a high osmotic concentration of the nutrient solution. An EC device, commercially available, should be used to determine the rate at which the nutrient solution becomes concentrated. Determinations should be made on a new nutrient solution and then repeated after each makeup with nutrient salts. As the total salt level increases, it will more readily conduct an electric current. The unit of measurement used to express conductance is a *mho.* For simplicity, conductivity is often expressed as millimhos (mmho) per centimeter, with the desired range 2.00–4.00. Salt levels above 4 mhos/cm

may result in wilting, suppressed growth, and fruit cracking [1 mmho/cm = 1 milliSiemen/cm (mS/cm)].

The total concentration of elements in a nutrient solution should be between 1,000 and 1,500 ppm so that osmotic pressure will facilitate the absorption processes by the roots. This should correspond to total salt conductivity readings between 1.5 and 3.5 mmhos. In general, the lower values (1.5–2.0 mmho) are preferred for crops such as cucumbers, while higher values are better for tomatoes (2.5–3.5 mmho). (A conductance of 1 mmho/cm is approximately equal to 650 ppm of salt.)

While in the past we recommended complete replacement of nutrient solutions after 2 mo, new systems of sterilization in recirculating systems and computer monitoring and adjusting of the solutions for ions and *p*H have favored keeping the solutions much longer. This has come about because of the need to conserve water and lessen contamination of the environment, groundwater, and surface water, especially in countries such as Holland (Van Os, 1994). But this is possible only with very pure raw water sources or after water treatment by reverse osmosis (RO) to eliminate extraneous trace elements and sodium chloride.

Closed (recirculating) systems always run the risk of disease infection, so efficient disinfection must be part of the system. Disinfection is a combination of pasteurization, slow sand filtration (biofiltration), UV radiation, and other methods as discussed in Section 12.7.

3.9.4 Adjustment of Nutrient Solutions by Use of Electrical Conductivity

Total dissolved solutes (TDS) instruments, which determine the dissolved solids in water, are basically water conductivity measuring instruments. The quantity of dissolved solids in parts per million (ppm) or milligrams per liter by weight is directly proportional to conductivity in millimhos per unit volume. However, the EC varies not only with the concentration of salts present but also with the chemical composition of the nutrient solution. Some fertilizer salts conduct electric current better than others. For instance, ammonium sulfate conducts twice as much electricity as calcium nitrate and more than three times that of magnesium sulfate, whereas urea does not conduct electricity at all. Nitrate ions do not produce as close a relationship with EC as do potassium ions (Alt, D. 1980). The higher the nitrogen to potassium ratio, the lower the EC values for the nutrient solution. EC measures total solutes; it does not differentiate among the various elements. For this reason, while a close theoretical relationship exists between TDS and EC, standard solutions of a nutrient formulation should be measured to determine their correlation in a given solution. For example, in Table 3.10 a 666-ppm TDS is equivalent to 1.0 mmho, which is the measurement of a solution containing 490 ppm of sodium chloride or 420 ppm of calcium carbonate. That is, a 490-ppm solution of sodium chloride or a 420-ppm solution of calcium carbonate each give an EC reading of 1.0 mmho.

Table 3.10 relates concentration of sodium chloride and calcium carbonate with conductivity. A list of conductivities for 0.2% solution (2 g of fertilizer in 1 L of distilled water) of various fertilizers is given in Table 3.11.

Conductivities for various concentrations of calcium nitrate are outlined in Table 3.12. These conductivity standards should be used to derive a theoretical relationship between conductivity and TDS. Actual conductivity measurements for fertilizers may vary somewhat from those in Tables 3.11 and 3.12 because of the solubility and purity of the particular fertilizer source. If EC readings are not taken at the standard temperature of 25^0C, a correction factor must be used (Table 3.13). Many conductivity meters have a built-in temperature compensation, which automatically makes the necessary adjustment. Several plant laboratories capable of analyzing nutrient solutions are listed in Appendix 2. In addition, many universities are prepared to do such analyses.

TABLE 3.10
Relationship between Total Dissolved Solutes (TDS) and Electrical Conductivity (EC) for Sodium Chloride and Calcium Carbonate Solutions

TDS (ppm)	EC (mmho)	NaCl (ppm)	$CaCO_3$ (ppm)
10,000	15	8,400	7,250
6,600	10	5,500	4,700
5,000	7.5	4,000	3,450
4,000	6	3,200	2,700
3,000	4.5	2,350	2,000
2,000	3	1,550	1,300
1,000	1.5	750	640
750	1.125	560	475
666	1	490	420
500	0.75	365	315
400	0.6	285	250
250	0.375	175	150
100	0.15	71	60
66	0.10	47	40
50	0.075	35	30
40	0.06	28	24
25	0.0375	17.5	15
6.6	0.01	4.7	4

TABLE 3.11
Conductivity (EC) of 0.2% Solution in Distilled Water

Fertilizer Compound	EC (mmho)
$Ca(NO_3)_2$	2.0
KNO_3	2.5
NH_4NO_3	2.9
$(NH_4)_2SO_4$	3.4
K_2SO_4	2.4
$MgSO_4 \cdot 7H_2O$	1.2
$MnSO_4 \cdot 4H_2O$	1.55
NaH_2PO_4	0.9
KH_2PO_4	1.3
HNO_3	4.8
H_3PO_4	1.8

The management of nutrient solutions through the use of EC applies particularly to closed systems of nutrient film technique (NFT) and subirrigation. However, it can be used to monitor open systems having large storage tanks of solution rather than those using proportioners.

Today, all modern greenhouses with hydroponic systems are reusing the leachate and operating as closed systems with *p*H and nutrient solution concentration monitored by *p*H and EC meters

TABLE 3.12
Conductivity (EC) of Various Concentrations of Calcium Nitrate in Distilled Water

Concentration (%)	EC (mmho)
0.05	0.5
0.1	1.0
0.2	2.0
0.3	3.0
0.5	4.8
1.0	9.0

TABLE 3.13
Temperature Factors for Correcting Conductivity Data to Standard Temperature of 25°C

Degree Centigrade	Degree Fahrenheit	Temperature Factor
5	41.0	1.613
10	50.0	1.411
15	59.0	1.247
16	60.8	1.211
17	62.6	1.189
18	64.4	1.163
19	66.2	1.136
20	68.0	1.112
21	69.8	1.087
22	71.6	1.064
23	73.4	1.043
24	75.2	1.020
25	**77.0**	**1.000**
26	78.8	0.979
27	80.6	0.960
28	82.4	0.943
29	84.2	0.925
30	86.0	0.907
31	87.8	0.890
32	89.6	0.873
33	91.4	0.858
34	93.2	0.843
35	95.0	0.829
40	104.0	0.763
45	113.0	0.705

Source: From *Saline and Alkali Soils,* U.S. Salinity Laboratory Staff, Agricultural Handbook, 1954, No. 60, p 90.

that feedback to a central computer controller that adjusts the return solution with injectors from stock tanks of acid/base and concentrated nutrient solutions (stock solutions) as discussed above in Sections 3.7.2 and 3.9.3 and in Section 12.7.

3.9.5 Maintenance of the Solution Volume

The solution volume must be kept relatively constant in order to secure adequate plant growth. Plants take up much more water than the essential elements, and at a much greater rate. As water is removed from the nutrient solution, the volume of the solution naturally decreases. This affects an increase in the total solution concentration and in the concentration of the individual nutrient ions.

The average daily water loss can range from 5% to 30%, depending on the volume of the unit and the number and type of plants. Water to compensate for this loss can be added daily as long as the solution is used. Using NFT systems, workers can more accurately determine the rate of water uptake by plants. In England, Spensley and coworkers (1978) found that on a clear summer day fully grown tomatoes consumed 1.33 L (1/3 gal) of water per plant. Winsor and associates (1980) determined that tomato plants lost through evapotranspiration 15 mL/plant/h during the night, rising to a maximum of 134 mL/plant/h at midday on a clear summer day. Adams (1980) calculated that cucumbers consumed water at approximately twice the rate for tomatoes because of their greater leaf area. Water uptake reached a maximum of 230 mL per plant per hour during maximum light intensity and temperatures of the afternoon. A rule-of-thumb estimate of water usage in a greenhouse is about 1 L/ft^2/d for vine crops such as tomatoes and cucumbers. Experienced commercial growers can add water weekly, or they can attach an automatic float valve assembly to the inlet valve to the nutrient tank, which will fill it daily. When water is added weekly, water in excess of the original volume of the solution is introduced. The solution is then allowed to concentrate as the plants remove water to below the original solution level. Usually, the best procedure is to allow the solution volume to fluctuate equally on both sides of the original level. It follows that a solution testing technique must be used in conjunction with the method of regulation of the solution volume. This applies to closed systems in which the solution is recirculated to a nutrient tank or cistern.

Most greenhouses today, however, as described later in Section 12.7 of Chapter 12, use return storage tanks, treatment systems, and storage of treated solution. From there as it returns to the plants it is monitored and adjusted by injection systems. This system is a dynamic flow-through system, so the adjusted nutrient solution is not stored before returning to the plants as it is in some NFT systems and simplified cistern return tanks as described above. This blended raw water (about 70%) and treated return solution (30%) from storage tanks enters an injection loop on its way back to the plants.

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4 The Medium

A soilless medium, such as water, foam, gravel, rockwool, sand, sawdust, peat, coco coir, perlite, pumice, peanut hulls, polyester matting, or vermiculite must provide oxygen, water, nutrients, and support for plant roots just as soil does. The nutrient solution will provide water, nutrients and, to some extent, oxygen. How each of these soilless cultural methods satisfies plant needs will be discussed in detail in the chapters that follow.

4.1 MEDIUM CHARACTERISTICS

Moisture retention of a medium is determined by particle size, shape, and porosity. Water is retained on the surface of the particles and within the pore space. The smaller the particles, the closer they will pack, the greater the surface area and pore space, and hence the greater the water retention. Irregular-shaped particles have a greater surface area and hence higher water retention than smooth, round particles. Porous materials can store water within the particles themselves; therefore, water retention is high. While the medium must be capable of good water retention, it must also be capable of good drainage. Therefore, excessively fine materials must be avoided so as to prevent excessive water retention and lack of oxygen movement within the medium.

The choice of medium will be determined by availability, cost, quality, and the type of hydroponic method. A gravel subirrigation system can use very coarse material, whereas a gravel trickle-irrigation system must use a finer material (Chapter 7).

The medium must not contain any toxic materials. Sawdust, for example, often contains high sodium chloride content because of logs having remained in salt water for a long period. The salt content must be tested, and if any amount of sodium chloride is present, it will be necessary to leach it through with fresh water. Similarly, coco coir, which comes from coconut trees, often contains high concentrations of sodium chloride when its source comes from trees near the ocean. Most coco coir sold as a substrate for hydroponic culture is treated to remove the salt. If not, it must be soaked well in clean raw water to leach out the sodium chloride. This can usually be done by soaking it in good quality water for a number of hours and then flushing several times with new water. Drain the coco coir well after soaking in water to remove the sodium and chloride.

Gravel and sand of calcareous (limestone) origin should be avoided. Such materials have a very high content of calcium carbonate ($CaCO_3$), which is released from the medium into the nutrient solution, resulting in high *p*H. This increased alkalinity ties up iron, causing iron deficiency in plants. Such materials can be pretreated with water leaching or acid leaching or by soaking in a phosphate solution. This will buffer the release of carbonate ions. Nonetheless, this procedure is only a short-term solution, and eventually nutritional problems will arise. This problem makes gravel and sand culture very difficult in some areas, such as the Caribbean, where the materials are all of calcareous origin. The best gravel or sand is that of igneous (volcanic) origin.

The media must be of sufficient hardness in order to be durable for a long time. Soft aggregates that disintegrate easily should be avoided. They lose their structure and their particle size decreases, which results in compaction leading to poor root aeration. Again, aggregates of granitic origin are best, especially those high in quartz, calcite, and feldspars. In a hydroponic system is to be set up outdoors, particles having sharp edges should be avoided, since wind can abrade the plant stem and crown against them, leading to injury and a port of entry for plant parasites. If a relatively sharp medium must be used, the top 2 in. (5 cm) should consist of smooth-edged medium so that the area where most plant movement takes place will be protected from abrasion.

DOI: 10.1201/9781003133254-4

Igneous gravel and sand have little influence on the nutrient solution *p*H, whereas calcareous material will buffer the nutrient solution *p*H at about 7.5. Treatment with phosphate solutions can bring the *p*H down to 6.8 (Chapter 7).

4.2 WATER CHARACTERISTICS

The water quality is of prime concern in hydroponic growing. Water with sodium chloride content of 50 ppm or greater is not suitable for optimum plant growth. As sodium chloride content is increased, plant growth is restricted; high levels result in the death of the plant. Some plants are less sensitive to salt levels than others. For instance, herbs, such as watercress and mint tolerate higher levels of sodium and chloride than do tomatoes and cucumbers. The levels of sodium chloride and other extraneous ions present in raw water as a source for a nutrient solution becomes even more critical in closed (recirculation) systems. These systems add raw water to the return solution to make up for the loss due to evapotranspiration by the plants. With continued addition of raw water, more ions will be added if the raw water contains significant levels, which will eventually lead to toxicity.

Hardness is a measure of the carbonate ion (HCO_3^-) content. As mentioned earlier, as hardness increases (*p*H increases), certain ions such as iron become unavailable. In particular, ground water that lies in calcareous and dolomitic limestone strata could contain high levels of calcium and magnesium carbonate, which may be higher than or equal to the normal levels used in the nutrient solution.

Hard water contains salts of calcium and magnesium. Normally such waters are just as suitable as soft water for growing plants. Both calcium and magnesium are essential nutrient elements, and ordinarily the amount present in hard waters is much less than that used in nutrient solutions. Most hard waters contain calcium and magnesium as carbonates or sulfates. While the sulfate ion is an essential nutrient, carbonate is not. In low concentrations, carbonate is not injurious to plants. In fact, some carbonate and/or bicarbonate in the raw water is helpful in stabilizing the *p*H of the nutrient solution. The carbonate or bicarbonate found in most waters causes the *p*H to rise or remain high. With the presence of these ions, the *p*H resists dropping.

This stabilizing effect is called *buffering capacity*. Smith (1987) advises to take advantage of this buffering action on *p*H by maintaining the carbonate/bicarbonate level at about 30–50 ppm, which is sufficient to prevent sudden fluctuations in *p*H. With very pure raw water, having little or no carbonate or bicarbonate, he suggests adding some potassium carbonate or bicarbonate to obtain this level to improve the buffering capacity.

Before any water is used, an analysis should be made for at least calcium, magnesium, iron, boron, molybdenum, carbonate, sulfate, and chloride. If a commercial hydroponic complex is being planned, water should be analyzed for all major and minor elements. Once the level of each ion has been determined, correspondingly less of each of these elements should be added to make up the nutrient solution. For example, the magnesium concentration of some well waters is so high that it is not necessary to add any to the nutrient solution. In some cases, boron may be excessively high (normal required is 0.30 mg/L) up to 2–3 times or more; then it must be removed through reverse osmosis (RO) treatment of the water.

The naturally occurring dissolved salts in the water accumulate with the additions of makeup water. Over a period of time, this buildup will exceed the optimum levels for plant growth, and the nutrient solution will have to be changed to avoid injuring the plants. This is particularly applicable to recirculating hydroponic systems in which the solution may be used for long periods of time. Raw water is added as the plants use the water in metabolic processes. The raw water will constantly add any extraneous salts such as sodium and chloride. The plants use small amounts of these elements. As a result, any raw water with relatively high amounts of these elements will accumulate in the nutrient solution, since the plants are not using up the levels between top-ups. For this reason,

commercial greenhouses using recirculation of leachate from the crop system need to use RO on the raw water source.

The total concentration of a nutrient solution or water source is occasionally specified in terms of its potential osmotic pressure. It is a measure of the availability or activity of the water. The osmotic pressure difference between cells usually determines the direction in which water will diffuse. The osmotic pressure is proportional to the number of solute particles in solution and depends on the number of ions per unit volume for inorganic materials. Osmotic pressure is usually given in atmosphere units, where 1 (atm) atmosphere is 14.7 lb/in.^{2} or 101.3 kPa (kilopascals).

The use of saline water for hydroponic growing of crops has been investigated by several workers (Schwarz, 1968; Victor, 1973). The possibilities of using saline water of 3,000 ppm total salt were investigated by Schwarz (1968). Salt tolerance of varieties, stage of development, addition of nutrients absent in the raw water, and frequency of irrigation are some factors to consider in using saline water. The concentration expressed by 0.4 atm osmotic pressure was recommended as the best for good development of tomato plants in tropical areas (Steiner, 1968).

Saline waters are those containing sodium chloride. Highly saline water can be used for hydroponics by use of reverse osmosis (RO) equipment. If a recycling hydroponic system is used on long-term crops, such as vine crops, the tolerable level of sodium and chloride in the raw water is much lower because of their build-up by continual topping up of the nutrient solution. The addition of raw water containing even 50 ppm of sodium chloride will become toxic to the plants over weeks of recirculation as each time the top-up raw water is added sodium chloride will be added and the plants will take up only small amounts of it, so the accumulation in the solution will reach levels of toxicity.

Symptoms of salt toxicity are a general stunting of growth with smaller and darker green leaves, marginal leaf burning, and a bluing and bleaching of the plant tissues. Salinity may inhibit uptake of certain ions. High sulfate concentrations promote the uptake of sodium (leading to sodium toxicity), decrease the uptake of calcium (leading to calcium deficiency, especially in lettuce), and interfere with potassium uptake. High calcium concentrations in nutrient solutions also affect potassium uptake. High total salt contents are thought to affect calcium uptake, leading to "blossom-end rot" symptoms in tomatoes. Saline conditions reduce the availability of certain microelements, especially iron, so that additional iron must be added. In addition to chloride and sodium toxicity, boron toxicity is relatively common with some saline waters.

4.3 IRRIGATION

The frequency of irrigation cycles depends on the nature of the plant; plant stage of growth; weather conditions (greenhouses), particularly light intensity, day length, and temperatures; and type of medium.

Plants that are more succulent with an abundance of leaves require more frequent irrigation, as they lose water rapidly through evapotranspiration from their leaves. The greater the leaf area, the more water they will consume. As plants mature, producing a large canopy of leaves and developing fruit, their water demand increases.

Under greenhouse conditions of high light intensity, generally accompanied by high temperatures, especially during summer months, the evapotranspiration rate of plants is greatly increased, and as a result water uptake also increases significantly. As pointed out in Section 3.9.5, researchers have found that a mature cucumber plant may take up as much as 230 mL of water per hour during midday conditions.

Water retention of the medium is a factor in determining the frequency and duration of irrigation. Finer media such as coco coir, peat, foam, or rockwool will retain more moisture than coarser ones such as sawdust, perlite, vermiculite, sand, or gravel. A water culture system, such as the nutrient film technique (NFT), must flow continuously to provide adequate water. In this case, only the plant

root mat contains a small amount of residual moisture should the flow of solution be interrupted. Coarse aggregates may need watering as often as once every hour during the day, while fine media such as coco coir and peat could get by on 1–2 irrigations per day under similar conditions.

Both the frequency and duration of irrigation cycles are important. The frequency of the cycles must be sufficient to prevent any water deficit for the plants between cycles, but the cycle must be long enough to provide adequate drainage of the medium so that proper oxygenation of plant roots occurs.

Wilting of plants indicates possible water deficit. However, root dieback caused by diseases, pests, or lack of oxygen can also cause wilting, so the health of the roots should always be examined when wilting occurs. Healthy roots will appear white, firm, and fibrous. No browning of sections or tips of roots should be present.

The duration of any given irrigation cycle must be sufficient to provide adequate leaching of the medium. With some of the finer media, such as rockwool, 20–30% runoff is needed to flush excessive nutrients through the substrate. If this is not done, salt levels will build up, causing slowing of growth or even toxicity in the plants. More specific details are presented for each type of hydroponic system in the following chapters.

4.4 PUMPING OF NUTRIENT SOLUTION INTO BEDS

As mentioned earlier, the nutrient solution must provide water, nutrients, and oxygen to the plants. The frequency of irrigation will depend on the nature of the medium, the size of the crop, and the weather conditions. To provide these plant needs most efficiently during each irrigation cycle, the solution must moisten the bed uniformly and drain completely and rapidly so that oxygen will be available to the plant roots.

Details of pumping frequency are discussed more thoroughly in the chapters on each soilless system. In all cases, free water must not remain in the medium. The voids (air spaces between the particles) should be filled with moist air, not water, in order to maintain oxygen concentration around the roots at high levels. In most systems, irrigation should be done mainly during the daylight hours, with only several or none at night (depending on the medium).

Ideally, moisture levels in the medium can be maintained at optimum levels through a feedback system. Such a system has a moisture-sensing device, such as a tensiometer or electrode, placed in the medium. This apparatus is connected to an electrical circuit that activates a valve or pump that waters the plants when the moisture falls below a preset level. In this way, optimum moisture conditions are maintained within a fairly narrow range of variation.

A good presentation of the relationship between solar radiation and irrigation is given by Broad (2008a, b). He explains that solar radiation is the main driver of transpiration by plants. He states that 70% of the sunlight passes through the greenhouse cover. Of the 70% that the plant receives, it reradiates 30%, so the plant absorbs only 50% of the total available light from the sun (70% x 70%) and uses that for transpiration. With large vine crops, therefore, 20% (30% x 70%) of the solar energy is left to heat the greenhouse air.

In greenhouse culture, the temperature of the nutrient solution in contact with the roots of plants should be maintained between 60°F and 65°F (15.5–18°C). Immersion heaters can be placed in the sump of smaller operations to heat the nutrient solution. Recent experiments have demonstrated that by heating the nutrient solution, air temperatures can be decreased to conserve heat in the greenhouses. During winter, some crops such as tomatoes grow better if the temperature of the root medium is maintained a few degrees above the average night air temperature.

In no case should heating lines or electric heating cables be placed in the bed itself. Such placement causes localized high temperatures around the heating elements, which injure the roots.

4.5 STERILIZATION OF MEDIUM

When crops are grown for extended periods in any substrate, soil-borne pathogenic microorganisms accumulate in the medium, and the chances of a disease occurring increase with each successive crop. It may be possible to grow several crops successively without sterilization in between; however, for best results the medium should be sterilized after each crop to prevent any possible disease carryover. The most common methods of sterilization use steam and chemicals.

If a greenhouse is heated by a central hot water or steam boiler, sterilization by steam would be the most economical. A steam converter attachment would be installed on the boiler and steam pipes run to the greenhouse with outlet attachments at each bed. A steam line is run down the center of each bed and covered with canvas or some heat-resistant material. Steam is then injected along the entire length of the bed at 180°F (82°C) for at least half an hour. This surface steaming is effective to a depth of 8 in. (20 cm) for sawdust beds but only to 4 in. (10 cm) for a 3:1 sand–sawdust mixture.

Today most greenhouses do not use beds, but raised gutters that support slabs of rockwool or coco coir (Chapters 10 and 11). To sterilize slabs, that may be used several times before disposal because of eventually structural breakdown, stack them on pallets or other supporting structures above steam lines that inject steam into the pile. The slabs must be moist in order to conduct heat throughout them. Arrange the layers of slabs so that they are crossed similar to how fertilizer bags are positioned on a pallet. Separate the slabs within each layer by crisscrossing them so that the steam can rise into the stack. Cover each lift of slabs on the pallets with canvas or other heat-resistant material to retain the heat within the pile. If the greenhouse is located in a desert or other hot climate, solar radiation could be effective. Make the piles 4 ft. x 4 ft. x 4 ft. tall (1.2 m x 1.2 m x 1.2 m) and cover them with black plastic. Locate them inside the empty greenhouse without ventilation operating or outside in a sun intense area. They could be left for a week or longer. Check the internal temperature of the slabs periodically to determine that it rises to 140–160°F (60–70°C). As long as this internal temperature lasts about an hour, the slabs will be sterilized.

Most chemical sterilization, apart from bleach, sodium hypochlorite, is no longer an approved method for sterilization in a greenhouse. Methyl bromide is prohibited; chloropicrin, Vapam, and Basimid are not recommended.

In gravel culture systems, common bleach (sodium or calcium hypochlorite) or hydrochloric acid can be used. A concentration of 10,000 ppm of available chlorine is made up in the sump tank and the beds are thoroughly moistened for half an hour. The beds must be thoroughly leached with fresh water to eliminate any chlorine before planting.

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5 Water Culture

5.1 INTRODUCTION

Of all the soilless methods, water culture, by definition, is true hydroponics. Water culture includes aeroponics. In aeroponic systems, plant roots are suspended into a closed dark chamber in which jets of nutrient solution are periodically sprayed over them to maintain 100% relative humidity. In water culture, plant roots are suspended in a liquid medium (nutrient solution), while their crowns are supported in a Styrofoam insulation cover as in the case of raft culture or by a plastic cover in the case of nutrient film technique (NFT). NFT is a form of water culture in which plant roots are contained in a relatively small channel through which a thin "film" of solution passes.

For successful operation a number of plant requirements must be met:

5.1.1 Root Aeration

This may be achieved in one of two ways. First, forced aeration (by a pump or compressor) is used to bubble air into the nutrient solution through a perforated pipe or airstone placed at the bottom of the bed and/or in the nutrient tank. Second, the nutrient solution is circulated with a pump through the beds and back to a reservoir. A series of baffles placed at the end of the beds will aerate the water as it returns to the reservoir. A rate of about 1–2 complete changes per hour is required for a bed 100 ft (30 m) long containing from 4–6 in. (10–15 cm) of nutrient solution (raft culture system). Best results can be achieved in a system in which the nutrient solution is pumped into the beds and allowed to flow past the plant roots continuously. In this way, freshly aerated solution will be in constant contact with the plant roots.

5.1.2 Root Darkness

Plants can function normally with their roots exposed to light during the daytime, provided they are always at 100% relative humidity. However, light will promote the growth of algae, which interferes with plant growth by competing for nutrients, reducing solution acidity, creating odors, competing for oxygen from the nutrient solution at night, and producing toxic products through its decomposition, which could interfere with plant growth. To eliminate algae growth, construct beds of or cover containers with opaque materials.

5.1.3 Plant Support

Plants may be supported by use of Styrofoam sheets or plastic covers in the case of NFT. This will also prevent light from entering the nutrient solution, and Styrofoam also acts as an insulating barrier against high temperatures.

5.2 RACEWAY, RAFT, OR FLOATING SYSTEM

Dr. Merle Jensen of the University of Arizona, Tucson, developed a prototype raceway lettuce production system during 1981–1982. He projected that such a system could produce 4.5 million heads of lettuce per year per hectare.

DOI: 10.1201/9781003133254-5

FIGURE 5.1 Raft system of Bibb lettuce. Lettuce from left to right is 4, 3, 2, and 1 d after transplanting. The first bed from the right was just harvested, the second is being cleaned and the third is ready to transplant. (From Hoppmann Hydroponics, Waverly, FL. With permission.)

The system consists of relatively deep (15–20 cm or 6–8 in.) beds holding a large volume of nutrient solution. The solution in the beds is fairly static, with a circulation of 2–3 L/min. The bed dimensions are about 60 cm wide by 20 cm deep by 30 m long (24 in. x 8 in. x 98 ft) (Figure 5.1). Such a bed has a volume of 3.6 m^3 (127 ft^3), which is equivalent to 3,600 L (about 950 US gal). Therefore, the flow through each bed at 2–3 L/min amounts to an exchange rate of 1 per 24-h period.

The nutrient solution from the beds is recirculated through a nutrient tank of 4,000–5,000 L (1,000–1,250 US gal). There the solution is aerated by an air pump, chilled with a refrigeration unit, and is then pumped back to the far ends of each bed.

On its return to the beds, the nutrient solution is passed through an ultraviolet sterilizer (Figure 5.2). These sterilizers are manufactured by several companies (Appendix 2) for use in soft drink, beer, distillery, aquaculture, clothing dye, and cosmetic industries, as well as those now specifically designed for commercial greenhouse applications. They are effective against many bacteria, fungi, viruses, and protozoa such as nematodes.

Evaluation of the effectiveness of a UV sterilizer against selected species of pathogenic and nonpathogenic fungi commonly associated with greenhouse crops by Mohyuddin in 1985 demonstrated that the unit significantly reduced or eliminated the following fungi from an aqueous solution: *Botrytis cinerea*, *Cladosporium sp.*, *Fusarium spp.*, *Sclerotinia sclerotiorum*, *Verticillium albo-atrum*, and several others.

Pythium infection of roots causes stunting of plants (Figure 5.3). Ultraviolet sterilization of nutrient solutions does not combat this disease organism. It can only be controlled by sterilization between crops of all beds, pipes, tanks, and so on with a 10% bleach solution.

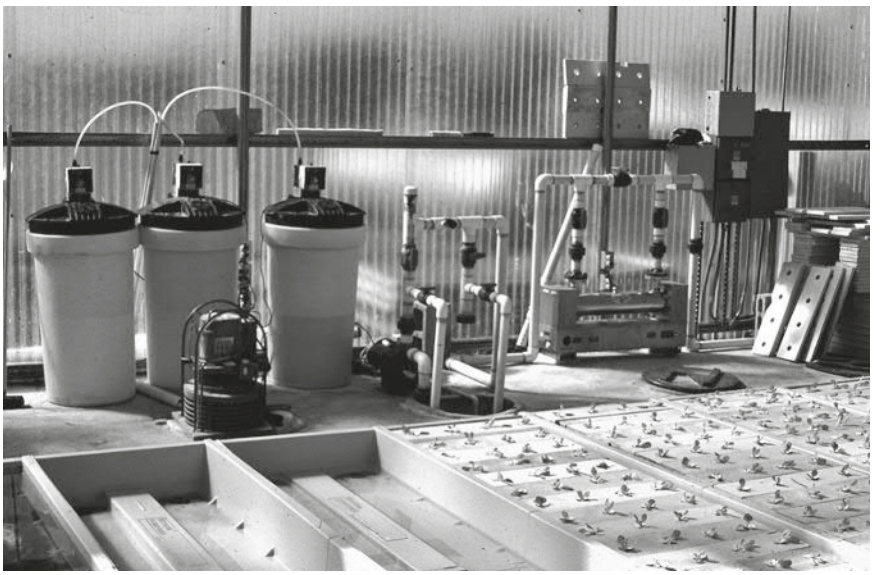

FIGURE 5.2 Raft system of water culture. Chiller unit on left in front of acid and stock-solution tanks with individual injectors. Circulation pumps in center and UV sterilizer on right. (From Hoppmann Hydroponics, Waverly, FL. With permission.)

FIGURE 5.3 *Pythium* infection of Bibb lettuce. Healthy plant on right, infected plant on left. Note: The difference in growth of the head and roots between the healthy and infected plants.

The cost of these sterilization units varies with their capacity. The larger the volume of water they can effectively treat, the larger the unit and higher the price. Prices for small units may be from $3,000 to $5,000, while larger Dutch systems can be well in excess of $50,000 for large-acreage greenhouses.

One side effect of the use of UV sterilizers is their effect on a few of the micronutrients. Mohyuddin (1985) found that the boron and manganese contents in a nutrient solution were reduced

by more than 20% over a period of 24 h of sterilization. The most significant effect was on iron, which was precipitated as hydrous ferric oxide. Nearly 100% of the iron was affected. The iron precipitate coated lines and the quartz sleeve of the sterilizer, thereby reducing the UV transmission. Such precipitate could be removed with a filter. Hydrogen peroxide injection prior to the solution passing through the UV sterilizer also improves effectiveness. However, the loss of iron from the nutrient solution during UV sterilization must be corrected downstream by addition of iron chelate.

The *p*H and electrical conductivity (EC) are monitored with sensors in the return line. Automatic injection of nitric acid (HNO_3), sulfuric acid (H_2SO_4), phosphoric acid (H_3PO_4), or potassium hydroxide (KOH) is used to adjust the *p*H. All of these variables are monitored and adjusted by a computer controller such as Argus or Priva (Appendix 2). Similarly, the EC is raised by injection of calcium nitrate and a mixture of the remaining nutrients from two separate stock concentrate tanks (Figure 5.2) to keep it at 1.2–1.3 mmhos.

It is also now standard practice when growing lettuce in a raft culture system to use a water chiller in the nutrient tank (Figure 5.2) to maintain temperature of the nutrient solution between 65°F and 75°F (18–23°C). This cooling of the nutrient solution will delay bolting of lettuce (lettuce going to seed) in desert and tropical regions.

5.2.1 Small- and Medium-Sized Commercial Raft Systems

European Bibb lettuce was grown commercially by Hoppmann Hydroponics, Ltd., Florida, at temperatures exceeding 110°F (43°C) in the greenhouses by use of the floating system using a water chiller in the nutrient tank.

Similarly, at CuisinArt Golf Resort & Spa, in Anguilla, British West Indies, in the Caribbean, various lettuces were grown at air temperatures of 90°F (32°C) using a raft culture system with chillers as shown in Figure 5.13, to maintain the nutrient solution temperature at 65°F (18°C). This temperature differential between the roots and upper part of the plant delays bolting by 3–4 d and also reduces fungal infection of the roots by *Pythium*.

Water-chiller units cool, aerate, and circulate the solution. They are available in one-sixth, one-half, and one horsepower units. The one-horsepower unit is capable of cooling 1,000 gal of water in a temperature range from 35–70°F (2–21°C). For nutrient solutions, units with stainless-steel drive shaft, evaporator tube, and circulator blade should be used. These units are used in aquarium tanks for the raising of fish.

Hoppmann Hydroponics produced Bibb lettuce on a 30- to 34-d cycle in the beds after transplanting (Figures 5.4 through 5.6). Lettuce can be sown using rockwool cubes, Jiffy pellets, or directly in a peat mix medium in plastic seeding trays. While rockwool cubes placed in 240-compartment trays are easily sown by automatic sowing equipment, the cost of rockwool is greater than that of using a peat mix in 273-compartment trays, which can also be sown automatically using pelletized seed.

Seedlings should be 12–14 d old before transplanting to the beds. The seedling trays can be bottom irrigated through the use of a capillary mat (Figure 5.7). This prevents overhead watering, which can burn the seedlings under extreme solar conditions of tropical and desert regions. Seedlings should be irrigated with a dilute nutrient solution when the cotyledons unfold. The capillary mats can either be replaced or sterilized between seeding crops (12–14 d) using a 10% bleach solution to eliminate algae, fungal spores, and insects such as fungus gnats.

Seeding and transplanting is carried out daily so that continuous production is achieved. Late evening transplanting after sunset will assure successful "take." Plants will have time to acclimate before full-light conditions of the following day. This is especially significant if transplants are bare rooted as is the case when the lettuce is sown in a peat medium. Bare-rooted plants are placed in paper supports, which are then placed in the 1-in. (2.5-cm) diameter holes of the Styrofoam "rafts" (Figure 5.8).

FIGURE 5.4 Lettuce 6 d after transplanting. The solution inlet pipe to the bed is in the foreground. Note: The wire hook attached to the first board (raft) to allow pulling of the boards during harvest.

FIGURE 5.5 Lettuce 12 d after transplanting.

This technique of starting the plants in a peatlite mix and then bare rooting to place in the rafts is no longer used, as it is more convenient to use rockwool or Oasis cubes to retain the roots without damaging during transplanting. These cubes can be placed in a normal plastic "flat" instead of the capillary matting tray used for the peat mix (peatlite) substrate.

In small greenhouse operations of 1 acre (0.45 ha) or less, the most common raft system is the use of "raceway" beds placed together over the entire floor area of the greenhouse such as was used at Hoppmann Hydroponics. The beds are about 2 ft (61 cm) wide by the length of the greenhouse. For example, the useable length of a greenhouse 120 ft (36.5 m) in length is about 108 ft (33 m).

FIGURE 5.6 Lettuce 32 d after transplanting. (From Hoppmann Hydroponics, Waverly, FL. With permission.)

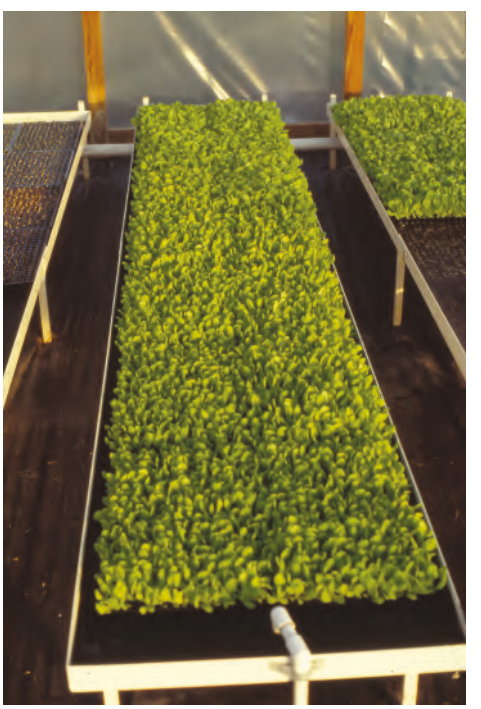

FIGURE 5.7 Lettuce seedlings, 10–12 d old.

In the beds are the "floats" or "rafts" of 1 in. x 6 in. x 24 in. (2.5 cm x 15 cm x 61 cm) boards of Styrofoam (Figure 5.9). The Styrofoam may be ordered in specific dimensions from the manufacturer if large quantities are purchased. They will cut the boards to the required dimensions with holes for placement of the plants. A high-density "roofmate" type of material (blue in color) used in house construction is most suitable.

FIGURE 5.8 Lettuce seedling being planted into 1-in. holes in "rafts." (From Hoppmann Hydroponics, Waverly, FL. With permission.)

FIGURE 5.9 "Raft" supporting four lettuce plants. Note: The vigorous healthy root growth. (From Hoppmann Hydroponics, Waverly, FL. With permission.)

FIGURE 5.10 Boat winch used to reel in boards. (From Hoppmann Hydroponics, Waverly, FL. With permission.)

The rafts insulate the underlying solution in the bed, and are a moveable system of transplanting and harvesting. Chillers were located in the nutrient tank, from where the solution was circulated into the beds that possess the largest volume of solution.

Maintenance of cool solution temperatures (optimum 70°F or 21°C) is a prime factor in preventing bolting of lettuce in hot climates. At the CuisinArt Golf Resort & Spa hydroponic farm in Anguilla in the Caribbean keeping the solution temperature about 65°F (18°C) under air temperatures of 90–95°F (32–35°C) delayed bolting of lettuce for 4–5 d.

The rafts simplify harvesting. A string placed under the rafts in the bed, attached to three or four wire hooks, which in turn are attached in several places to the rafts along the entire bed length, can be pulled in by a boat winch at the harvesting end of the greenhouse (Figures 5.4 and 5.10). The rafts float mature lettuce plants *in situ* within the beds. Easier flotation is possible by raising the solution level in the bed prior to harvesting, by plugging the return pipe of the nutrient-circulation system.

During transplanting, the boards are pushed along the bed from the harvesting end as the plants are placed in them (Figure 5.8). Long lines of floats with growing lettuce are readily moved.

Between crops, the boards must be cleaned and sterilized by hosing them with water prior to dipping them in a 10% bleach solution. Similarly, the beds must be drained and cleaned after each harvest (Figure 5.11). A new nutrient solution is prepared in the bed after cleaning and is ready for transplanting the same day.

Sowing, transplanting, and harvesting must be coordinated to get a continuous daily cycle. The growing period in the beds may vary from 28 to 35 d for Bibb lettuce, depending on sunlight and temperature conditions. In semitropical, tropical, and desert regions where sunlight is abundant and day length averages between 14 and 16 h, it is possible to obtain 10–12 crops annually, whereas in the temperate climates where sunlight is lower and day length may be 8 h or less during the winter months, it may only be possible to reach 7–8 crops annually. In temperate regions, winter crops may

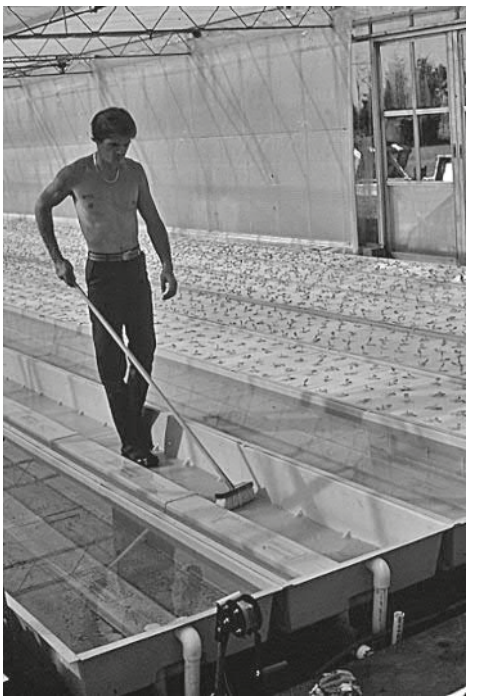

FIGURE 5.11 Beds are cleaned between crops. (From Hoppmann Hydroponics, Waverly, FL. With permission.)

take 13 wk (including 40 d from sowing seed to transplanting), whereas summer crops take 5 wk (including 12 d from sowing to transplanting). By use of supplementary artificial lights, the sowing to transplanting period could be shortened during winter to perhaps half the time.

Individual heads are packaged in plastic bags. Some growers leave about 1 in. of roots on the plants when packaging, with the expectation of longer shelf life than without roots. However, some consumers may not like the presence of roots. In Arizona (Collins and Jensen, 1983) the roots-on package did not increase shelf life, and it was found to be three times more expensive to prepare and pack. The roots-on packaging was not well accepted by wholesalers or retailers and added to the cost of transportation because of increased volume and weight. Generally, 24 heads are packaged in a case. It is now standard practice to leave the growing cube with some roots using special shaped clam-shell plastic containers.

The raceway system maximizes the usage of greenhouse floor space for production of lettuce or other low-profile crops. For example, a greenhouse of 1 acre (43,560 ft^2) with dimensions of 108 ft x 403 ft (33 m x 123 m) allowing front and back aisles of 8 ft (2.4 m) and 2 ft (0.6 m), respectively, with 2-ft access aisles every 29 ft (11 sets of beds), has a useable production area of 37,000 ft^2 (3,439 m^2). This is 84% utilization of greenhouse floor area. Such a growing area could produce 112,100 heads of lettuce per crop. That is, 2.6 heads per square foot (28 heads/m^2) of greenhouse area, or 3 heads per square foot (32 heads/m^2) of the available growing area.

Another method of raft culture for smaller greenhouse structures, for example, 30 ft x 120 ft (9 m x 36.6 m), is to construct beds 8 ft x 108 ft (2.4 m x 33 m). These are inside dimensions so that a standard 4 ft x 8 ft (1.2 m x 2.4 m) sheet of Styrofoam would fit inside the beds. The boards should be cut in half so that they are easier to handle during transplanting and harvesting. Beds could be constructed of concrete blocks or wood to obtain a minimum depth of at least 8 in. (20 cm). A 20-mil thick swimming pool vinyl liner is used to contain the solution. Each bed has a volume of about 3,000

FIGURE 5.12 Styrofoam boards with 64 heads of lettuce. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

US gal (11,355 L). Air stones, such as those used in aquaculture of fish, can be distributed along the bed length to aerate the solution. The stones may be connected by poly tubing to an air pump. A chiller could also be installed in each bed if lowering of the solution temperature is required. The bed layout would be to have three beds per greenhouse with 2-ft (61-cm) aisles between. If 6 in. x 6 in. (15 cm x 15 cm) spacing is used, each board 4 ft x 4 ft (1.2 m x 1.2 m) would contain 64 lettuce or basil. One bed would contain 27 full boards or 54 half boards having a capacity of 3,456 plants.

On a small scale, raft culture may be set up in ponds having dimensions in a multiple of 4 ft, as the Styrofoam sheets come in 4 ft. x 8 ft. (1.2 m x 2.4 m) size. Cut the sheets in half as indicated above for ease of handling. Each board will hold 64 head of lettuce (Figure 5.12).

At CuisinArt Golf Resort & Spa in Anguilla, two ponds were constructed. The dimensions of the ponds are 20 ft x 32 ft (6 m x 9.8 m) and 20 ft x 16 ft (6 m x 4.9 m). The sidewalls of the ponds were formed using two tiers of concrete blocks to achieve a depth of 1ft (30 cm). The bottom of the pond was sloped towards one corner where a circulation pump and two chillers were located (Figure 5.13). Initially, the pond was lined with 20-mil vinyl. However, since the pond was not rectangular, but had inside and outside corners, it made it very difficult to seal the angles of the vinyl. Continued water loss from the liner made it necessary to remove the vinyl liner and pour concrete with wire mesh on the base and grout the sides of the blocks. This was then treated with a concrete sealer such as "Thoroseal," which goes on as a thick paste. After that, a bituminous base paint used for foundations was applied. The important point is to make the pond rectangular, having only inside corners to enable using a vinyl liner. A circulation pump was connected to a 2-in.-diameter PVC pipe placed at the bottom inside corner around the pond with tees having a reducer to 0.25 in. located every 24 in. (61 cm) to aerate and mix the nutrient solution continuously, as shown in Figures 5.13 and 5.14.

After two consecutive crops, the lettuce pond is cleaned with a 10% bleach solution. The ponds are drained, and the lettuce boards containing young plants are removed and stacked with roots together board to board (Figure 5.14). In this way, the moisture is maintained in the roots while the ponds are being cleaned. In addition, they may be sprinkled with water every half hour to keep them from drying.

FIGURE 5.13 Circulation pump with chillers. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

FIGURE 5.14 Perimeter mixing pipe with tees. Note: Stacking of boards in background. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

The pond is cleaned by spraying the bleach solution using a back-pack sprayer and mopping it (Figure 5.15). The system is flushed by pumping the solution through the circulation pipes followed by flushing them with clean water before refilling the pond and making up the nutrient solution. This cleaning and changing of the nutrient solution takes about 1–2 h.

FIGURE 5.15 Sterilizing the lettuce pond. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

5.2.2 Large Commercial Raft Culture Systems

A world leader in large commercial raft culture greenhouses is Hydronov, Inc. They are based in Quebec, Canada with present headquarters in Ashley, IN. They started in 1982 as Bioserre, Inc. and then expanded to 2.7 ha (6.75 acres) in Mirabel, Quebec, as Hydroserre Mirabel, Inc. in 1987. In 1992, they expanded again with an additional 2.0 ha (5 acres) as Phase 2, as shown in Figure 5.16. In 1995, they incorporated a subsidiary, Hydronov, Inc., to market their hydroponic technology of "Floating Rafts Growing Technology," as turnkey operations for other locations in North America, Mexico, and worldwide.

They formed joint ventures in China with Shenzhen Evergreen Vegetable Co. Ltd. in 1998 and Beijing Evergreen Vegetable Co. Ltd. in 1999. They established a 1.5-ha (3.75-acre) greenhouse operation in Shenzhen, China, and another 1.5-ha (3.75-acre) greenhouse in Beijing as joint ventures (Figure 5.17).

They expanded operations in Quebec, Canada as Hydroserre Mirabel, Inc., Phase 3, in 2000 with 2.3 ha (5.75 acres) and continued developing more operations in China from 2001 through 2003: Shanghai Evergreen Vegetables Co. Ltd. in Shanghai of 1.5 ha (3.75 acres); Dalian Hualu Vegetables Co. Ltd. of 1.5 ha (3.75 acres) in Dalian, China; and Shenyang Huanji Elite Vegetables Co. Ltd. of 1 ha (2.5 acres) in Shenyang, China.

During the period from 2003 through 2008 they established 5.2 ha (13 acres) in Leon, Mexico, as Omnilife Hydroponic Greenhouses; 1.5 ha (3.75 acres) in Hiroshima, Japan as Japan Plantation Co. Ltd.-Nippon Noen; 1.0 ha (2.5 acres) in Shenyang, China; 5 ha (12.5 acres) in Livingston, Tennessee, in 2007 as Mirabel Inc. Hydroserre, and continued expanding in Quebec with two other 1.0-ha (2.5-acre) operations. The total area worldwide that Hydronov had established up to 2012 was close to 30 ha (75 acres). From 2013 to the present they have developed projects in Martinique, Lapallun SAS, 1.2 ha (3 acres) of Boston lettuce, Yardley, Pennsylvania, 0.5 ha (1.25 acres) of leafy greens in 2014; Southeast Asia 0.17 ha (0.43 acres) of leafy greens in 2015; Rochelle, Illinois, for Bright Farms, 1 ha (2.5 acres) of leafy greens in 2016 and 1 ha (2.5 acres) of leafy greens in Elkwood, Virginia. A 2.3 acre (0.95 ha) of leafy greens with Green Life Farms, Lake Worth, Florida,

FIGURE 5.16 Hydroserre Mirabel, Inc., Mirabel, Quebec, Canada. (From Hydronov, Inc. With permission.)

FIGURE 5.17 Shanghai Evergreen Vegetable Co. Ltd., greenhouse of 1.5 ha. (From Hydronov, Inc. With permission.)

was completed in 2019. In 2020, 1.5 ha (3.75 acres) in Taylorville, Illinois, for Clear Water Farms and in 2021, 1.2 ha (3 acres) were completed for Eden Valley in Franesville, Indiana.

Initially they specialized in producing Bibb or Boston lettuce and various European type leaf lettuces such as red and green oakleaf, Lollo Rossa, Lollo Bionda, and Batavia. As market demand changed for mesclun mixes, herbs and baby leafy greens, Hydronov develop specific boards and techniques for growing these products.

The more recent projects from 2014 to the present focused on high density leafy greens such as arugula, kale, romaine lettuce, spinach, and Swiss chard. They may be mixed to form blends and may include Asian greens. Herbs include Italian and purple basils, watercress, chervil, arugula, parsley, amaranth, mizuna, Asian greens, and medicinal herbs. They are attractively packaged in clam shell containers.

Hydronov claims that they achieve production levels up to 500 head (150–200 g/head) of lettuce per square meter (10.76 ft^2) per year. It takes about 45 d per crop, with 20 crops annually. They compare that to annual production of 36 plants per square meter in field production and 108 plants per square meter for normal greenhouse soil production.

They term their deep-water floating rafts technology "Floating Raft Technology" or FRT. The main advantage of their system is using mechanization to move plants from their growing area to harvesting or from seeding and transplanting. Workers do not have to bend over to perform their tasks, so back injuries are avoided. The plants in their boards move from the floating production area to an area of mechanical conveyors specially designed for seeding, transplanting, harvesting, packaging, and cooling. The number of workers needed per hectare varies from 5 to 15 depending on the crop, type of packaging, and level of mechanization. They claim with FRT, up to 18 crops annually of single head lettuce such as Boston, red and green oakleaf, Lollo Rosa, and so on, can be grown, with an average weight of 200 grams.

The cropping process for head lettuces is as follows:

5.2.2.1 Seeding

Seeds are sown by mechanical seeders into Oasis cubes placed in plastic flats. Trays containing the sheets of Oasis cubes are watered and then transported to a floating table bench system using Styrofoam boards underneath the seedling trays and irrigated with an overhead boom irrigator as shown in Figures 5.18 and 5.19. This is the germination stage.

FIGURE 5.18 Initial watering of sown flats of Oasis cubes. (From Hydronov, Inc., Omnilife Hydroponic Greenhouses, Leon, Mexico. With permission.)

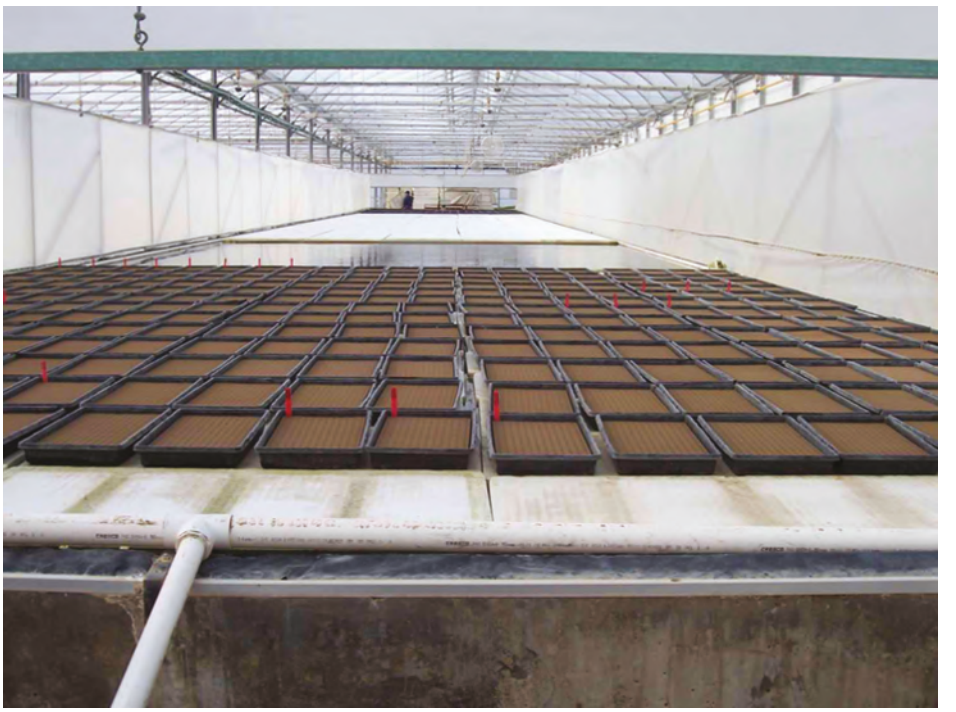

FIGURE 5.19 Sown trays of lettuce on a floating table system. (From Hydronov, Inc., Omnilife Hydroponic Greenhouses, Leon, Mexico. With permission.)

5.2.2.2 Transplanting

Once the seedlings have germinated (4–6 d and formed their first true leaf), they are transplanted to seedling Styrofoam boards that are then placed in the floating raft culture system. They are very closely spaced at this stage, with 288 seedlings per 2 ft x 4 ft board as shown in Figures 5.20 and 5.21.

The second transplant stage is at the third true-leaf stage, about 10–12 d from sowing. The exact time depends on the weather conditions. Under more sunlight and higher temperatures the growing period may be reduced by several days. In Figure 5.21, the plants in the foreground are much younger than those in the background. The second transplant is into boards 2 ft x 4 ft containing 72 seedlings (6 x 12). This is done at the transplanting station, and then the boards are moved by a conveyor belt to the raft pond location where they will grow during this second transplant stage as shown in Figures 5.22 through 5.24.

The seedlings are grown to their fourth true-leaf stage (about 18–21 d from sowing or 8–10 d from last transplant stage depending on weather conditions) before transplanting to the final growing stage (Figures 5.25 and 5.26). At this stage, 18 plants (3 x 6) are set in each board of 2 ft x 4 ft. The boards are then transported to the final growing raft pond and will be ready to harvest within another 24–30 d when they are harvested at about 45 d from sowing (Figure 5.27).

5.2.2.3 Harvesting

The mature lettuce is harvested from its board, which is picked up and transferred to a conveyor system that takes the board to the packing facility (Figure 5.28). A specialized winch pulls the boards toward the end where they are being set onto the conveyor system. The conveyor system contains water so that the rafts can float while being pulled by the chain links underneath, as can

FIGURE 5.20 Transplanting germinated seedlings in cubes to Styrofoam boards containing 288 seedlings. (From Hydronov, Inc., Omnilife Hydroponic Greenhouses, Leon, Mexico. With permission.)

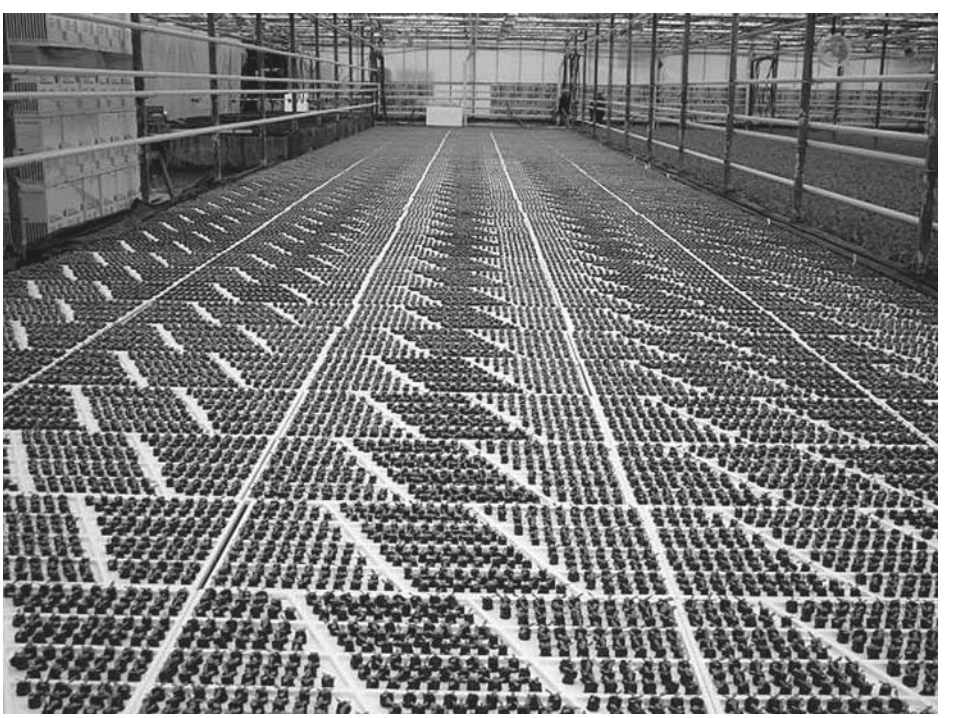

FIGURE 5.21 Transplanted stage 1 seedling boards. (From Hydronov, Inc., Hydroserre Mirabel Inc., Mirabel, Quebec, Canada. With permission.)

FIGURE 5.22 Transplanting stage 1 plants to stage 2, with 72 seedlings per board. (From Hydronov, Inc., Hydroserre Mirabel Inc., Mirabel, Quebec, Canada. With permission.)

FIGURE 5.23 Transplanted stage 2 plants on conveyor transporting to raft pond. (From Hydronov, Inc., Omnilife Hydroponic Greenhouses, Leon, Mexico. With permission.)

FIGURE 5.24 Seedlings at stage 2 in raft pond. (From Hydronov, Inc., Omnilife Hydroponic Greenhouses, Leon, Mexico. With permission.)

FIGURE 5.25 Seedlings in stage 2 ready to transplant to final growing boards. (From Hydronov, Inc., Hydroserre Mirabel, Inc., Mirabel, Quebec, Canada. With permission.)

FIGURE 5.26 Final transplant to growing boards of 18 plants per board. (From Hydronov, Inc., Shanghai Evergreen Vegetables Co. Ltd., Shanghai, China. With permission.)

FIGURE 5.27 Lettuce at about 45 d ready to harvest. (From Hydronov, Inc., Japan Plantation Co. Ltd.-Nippon-Neon, Hiroshima, Japan. With permission.)

FIGURE 5.28 Harvesting boards of lettuce and placing into the conveyor system for transport to the packing facility. Note: The winch system that pulls the boards in the growing raft pond toward the harvesting end. (From Hydronov, Inc., Japan Plantation Co. Ltd.-Nippon-Neon, Hiroshima, Japan. With permission.)

be seen in Figures 5.28 and 5.29. At the packing facility, the lettuce is removed, trimmed, placed in plastic clam shell containers, and either placed on another belt to go to the boxing area or boxed immediately at the same work station as shown in Figures 5.30 and 5.31. Once the lettuce is boxed, it moves to a rapid chilling (vacuum cooling) chamber and then into a cooler (Figure 5.32). The boards move on a conveyor from the packing area where the lettuce is removed to a board washing machine as seen in Figures 5.31 and 5.33. From there, the boards are returned to the planting area of the greenhouse to start the cycle over again.

The nutrient solution is recycled to a treatment area and then adjusted for *p*H and EC by use of injectors with stock solutions as shown in Figure 5.34. A typical greenhouse operation of 1.5 hectares or 3.75 acres in Japan is shown in Figure 5.35.

5.2.2.4 Hydronov Update

Hydronov has evolved into a design build General Contractor that works alongside clients through site selection, project design, construction, commissioning, on-site training, and grower support.

Hydronov claims there is an increasing demand for baby leaf product and the majority of new projects are growing on their high-density rafts. One of the key components driving this demand is lower labor costs. Because of the efficiency in machinery, fewer staff is required for a successful harvest. In addition, the high-density rafts/boards are easy to use and do not require specialized training.

Hydronov's high density leafy greens system uses special boards that have grooves in them for holding a peatmoss-vermiculite media mix. The grooves are in rows spaced closely together for the correct spacing of plants between rows and allows seed spacing within the rows as per the specific

FIGURE 5.29 Lettuce traveling on conveyor system to packing facility. Note: The winch that pulls the boards to the harvesting end of the lettuce raft pond. (From Hydronov, Inc., Omnilife Hydroponic Greenhouses, Leon, Mexico. With permission.)

FIGURE 5.30 Packing facility where the lettuce is removed from the boards, put in plastic clam-shell containers, and placed in boxes. (From Hydronov, Inc., Omnilife Hydroponic Greenhouses, Leon, Mexico. With permission.)

FIGURE 5.31 Removing lettuce from boards and boxing in the packing area. The board washing machine is on the left. (From Hydronov, Inc., Hydroserre Mirabel Inc., Tennessee, Livingston, TN. With permission.)

FIGURE 5.32 Boxed lettuce moving through a vacuum cooler. (From Hydronov, Inc., Hydroserre Mirabel Inc., Tennessee, Livingston, TN. With permission.)

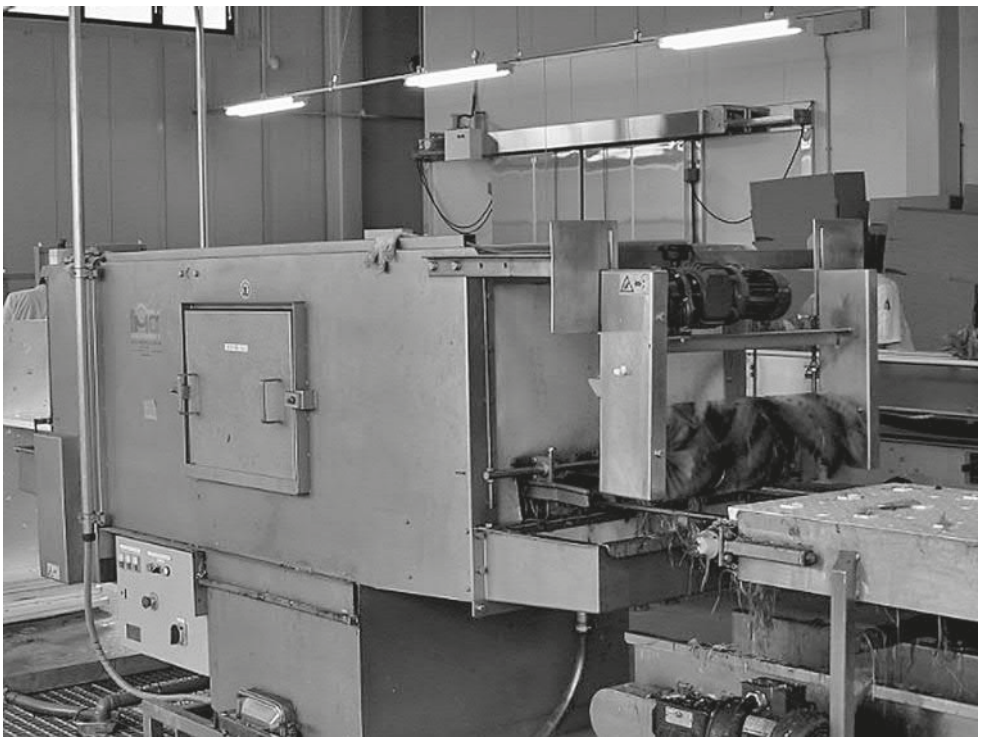

FIGURE 5.33 Board washer to clean and sterilized the boards. (From Hydronov, Inc., Japan Plantation Co. Ltd.-Nippon-Neon, Hiroshima, Japan. With permission.)

FIGURE 5.34 Adjustment of the nutrient solution using an injection system. (From Hydronov, Inc., Japan Plantation Co. Ltd., Nippon-Neon, Hiroshima, Japan. With permission.)

FIGURE 5.35 Hydronov, Inc., Japan Plantation Co. Ltd., Hiroshima, Japan. (From Hydronov, Inc., Quebec, Canada. With permission.)

leafy green crop grown. The high-density boards are designed for baby leaf mixes as well as basils, watercress, mache, spinach, arugula, beet, chicory, kale, mizuna, culinary, and medicinal herbs.

The growing process starts with filling the board channels with medium by a special automated flat filling machine, followed by automated seeding as shown in Figures 5.36 and 5.37. The boards are stacked and placed in a special germination room for 2 d as shown in Figure 5.38.

After the seeds have germinated (Figure 5.39) the boards are moved to the FRT production pool area (Figure 5.40) on the third day.

At 25 d the leafy greens are ready to harvest (Figure 5.41). The harvestable boards are moved to the end of the pond and placed onto a belt that transports them to the processing-packing facility (Figure 5.42 and 5.43). The boards of leafy greens go to the processing area where they are automatically cut and sent for packaging (Figure 5.44).

The boards then move to a washing machine (Figure 5.45) where they are washed and sterilized for re-use. The entire growing process is then repeated.

5.3 AEROPONICS

Aeroponics is the growing of plants in an opaque trough or supporting container in which their roots are suspended and bathed in a nutrient mist rather than a nutrient solution. This culture is widely used in laboratory studies in plant physiology, but not as commonly used as other methods on a commercial scale. It is possible to grow low-profile plants, including strawberries, lettuce, arugula, basil, and many herbs, but may not be economically feasible because of high capital costs of such commercial systems. It is applicable to crops whose harvestable portion is high value roots or tubers.

FIGURE 5.36 Automatic seeder. (From Hydronov, Ashley, IN. With permission.)

FIGURE 5.37 Sowing of seeds into boards with medium. (From Hydronov, Ashley, IN. With permission.)

FIGURE 5.38 Sown boards placed in germination room for 2 d. (From Hydronov, Ashley, IN. With permission.)

FIGURE 5.39 Germinated seeds in board. (From Hydronov, Ashley, IN. With permission.)

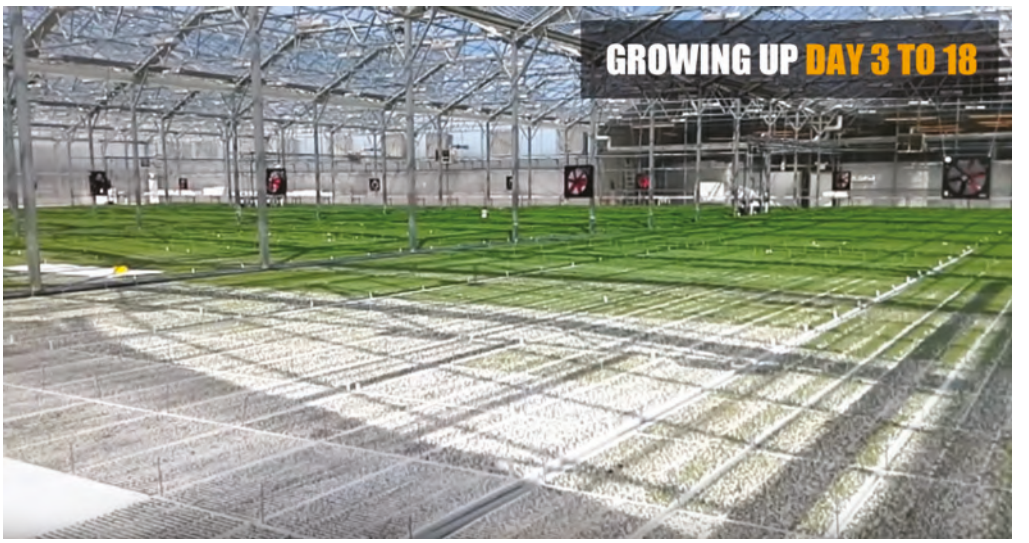

FIGURE 5.40 Boards from front to back are 3 d to 18 d. (From Hydronov, Ashley, IN. With permission.)

FIGURE 5.41 Baby greens ready to harvest. (From Hydronov, Ashley IN. With permission.)

FIGURE 5.42 Leafy greens ready to harvest at 25 d are floated to the end of the pond where they are removed and placed on a conveyor belt to go to the packing facility. (From Hydronov, Ashley, IN. With permission.)

FIGURE 5.43 Bibb lettuce ready to harvest move on a belt to processing area, which is the same procedure for the leafy greens. (From Hydronov, Ashley, IN. With permission.)

FIGURE 5.44 Harvesting unit that cuts the leafy greens from the boards. (From Hydronov, Ashley, IN. With permission.)

FIGURE 5.45 The washing unit where boards are cleaned and sterilized. (From Hydronov, Ashley, IN. With permission.)

A number of commercial ventures are using aeroponics for the growing of medicinal plants whose end product is in the roots. Seed potatoes that must be free of any diseases are being grown in an aeroponic system at the International Potato Research Center at Universidad de La Molina in Lima, Peru (Figures 5.46 and 5.47). The research center ships certified seed potato tubers worldwide as mother plants for local planting. The seed potatoes are a very high-value crop for introducing seed stock certified free of diseases to various countries.

The best location to visit futuristic agriculture using hydroponics and aeroponics is "The Land Pavilion," located in "Future World" in Epcot at the Walt Disney World Resort near Orlando, Florida. Epcot houses the Land Pavilion. With the "Living with the Land" boat tour in the experimental greenhouses, a special "behind the scenes" tour can be taken to visit the various hydroponic and aeroponic displays.

Several types of aeroponic systems are demonstrated, the A-frame system and the moveable overhead rail system. The A-frame is constructed of Styrofoam board sides supported by a frame above a nutrient reservoir (Figure 5.48). The plants are inserted into the holes of the Styrofoam sides with their roots suspended on the inside. High pressure misting nozzles spray the solution onto the roots from below, and the excess solution drains back to the tank. The roots of the plants get good oxygen from the spray of solution and from the volume of air within the chamber. This type of system is best used for lettuce, herbs, and medicinal plants whose roots would be harvested for the commercially active ingredient used for vitamins or drugs.

An overhead aeroponic culture system is a moveable rail supporting columns of herbs and ornamentals that move around the display area (Figures 5.49 and 5.50). They are misted with nutrient solution from the top of the column and permitted to drain below.

FIGURE 5.46 Aeroponic growing of seed potatoes. (From the Potato Research Center, Universidad de La Molina, Lima, Peru. With permission.)

FIGURE 5.47 Aeroponic seed potatoes. Note: The small tubers on the roots. (From the Potato Research Center, Universidad de La Molina, Lima, Peru. With permission.)

FIGURE 5.48 Cabbage growing in aeroponic A-frame system. Note: The misting system below in the nutrient tank. (From Epcot, near Orlando, FL. With permission.)

FIGURE 5.49 Herbs in moveable rail supporting columns. Cabbage in A-frame behind. (From Epcot, near Orlando, FL. With permission.)

FIGURE 5.50 Hot peppers in moveable column. Nasturtiums behind. (From Epcot, near Orlando, FL. With permission.)

5.4 HYDROPONIC GRASS UNITS

The growing of grains with a nutrient solution within an enclosed environmentally controlled chamber or unit has become of commercial significance as a source of year-round fresh grass feed for animals (Arano, 1998).

Grains such as oats, barley, rye, wheat, sorghum, or corn are presoaked for 24 h before being placed in growing trays (about 0.5 m^2) for 6 d. The trays may be watered manually on shelves with excess nutrient solution draining to waste, or the entire system of trays may be mounted on rotating drums that are automatically fed with a nutrient solution, which is recycled. Light is provided artificially by use of cool-white fluorescent lighting. After 6 d of growth, the grain (grass) has grown to 4–5 in. (15–20 cm) and is ready for harvesting and feeding to the animals.

Various commercial grass-growing units have been available in a number of sizes. A 20-ft long by 8-ft high by 10-ft wide (6.0 m x 2.4 m x 3.6 m) unit is shown in Figure 5.51.

In this unit, a four-fold bank of six layered trays separated by about 30 cm (12 in.) rotates under artificial lighting. Each layer has a set of five trays, 0.9 m x 0.45 m (36 in. x 18 in.), giving a total area per layer of 2.0 m^2 (22.5 ft^2). Into each layer (five trays) about 11.3 kg (25 lb) of grain is placed daily. The temperature is maintained at 22–25°C (72–77°F) and the relative humidity at 65–70%.

The unit of four banks of 30 trays is said to produce up to one-half ton (450 kg) per day of fresh green grass from 100 lb (45 kg) of grain. The grass is fed to animals in its entirety – roots, seeds, and green foliage.

The cropping schedule is set up so that one series of trays is harvested each day and at the same time one series is also seeded. In this way, continuous production 365 d a year is possible.

It is stated (Arano, 1976a) that each kilogram (2.2 lb) of grass is equivalent nutritionally to 3 kg (6.6 lbs.) of fresh alfalfa. Arano also states that 16–18 kg (35–40 lb) of grass is sufficient as the daily food requirement for one cow in milk production.

He speculates that a standard grass-growing unit of six separate tiers, each having 40 trays, could feed 80 cows all year. In a test of milk production with a diet of grass versus one of normal feed (such as grain, hay, and silage), the group of 60 cows on the grass diet increased their milk production by 10.07% over those on the normal diet. In addition, the group fed on grass produced a butterfat content of 14.26% higher than those fed the regular diet.

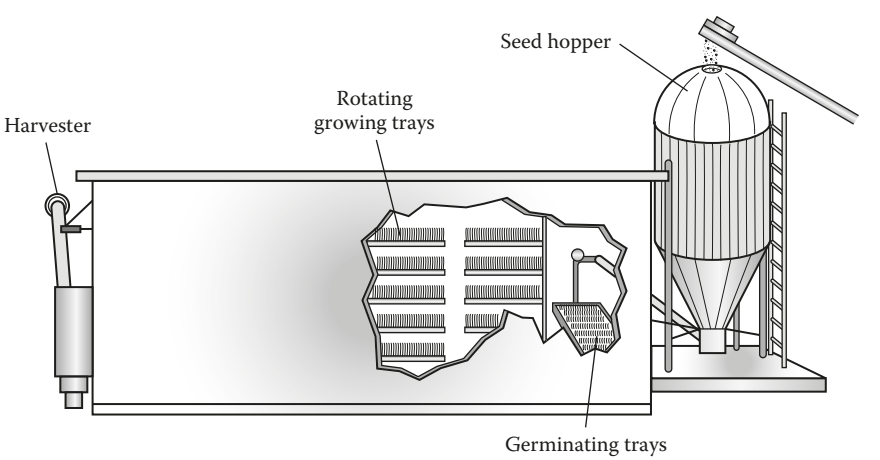

FIGURE 5.51 An automatic commercial grass-growing unit. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

The grass-growing units have proven to be beneficial to other animals besides dairy cows. Race horses fed on grass performed better, and zoo animals, which are accustomed to a grass diet in their normal habitat, were healthier in confinement when fed fresh grass year-round.

Evidence is given (Arano, 1976b) that the hydroponic grass units produce animal feed at about one-half the cost of that produced conventionally. This is based on the larger amounts of fuel needed in the production and transportation of traditional animal feeds. The grass-growing units enable animal producers to grow feed year round *in situ.* No storage of hay or silage is necessary since fresh grass is produced daily. This grass can be grown in a very small area compared to field-grown grasses and feeds. Costs of insecticides, fertilizers, machinery for cultivation and harvesting, and labor of field-grown feeds are estimated to be at least 10 times greater than that of hydroponically grown grass.

An inexpensive grass unit has been established in Peru by Sr. Enrique Valdavia Benavides (1997) to supply green fodder to beef and milk cattle. This is particularly important in an arid area where fresh grass is unavailable. An enclosed structure with roof vents to allow cooling and partially open sides to permit light to enter is adequate to house the trays tiered on shelving. In the Peru operation, seven levels of shelving were used to support the trays. Above each level is a series of mist nozzles to supply water and nutrients as the seeds grow.

Seeds are washed to remove impurities and poor seeds, and then imbibed by soaking in a tank for 18–24 h depending on the temperatures. Less time is required under higher temperatures. Imbibed seed is then partially dried 24 h in wooden boxes. All boxes, tanks, and so on must be sterilized before each use. When moving the imbibed seed to the germination trays, care must be taken not to damage the developing radicals.

The seeds are placed in the trays to a depth of about 1.5 cm (Figure 5.52). The seed trays are placed in a production room on shelving with a mist system where they will remain for 6–7 d (Figure 5.53). Watering cycles range from 8 to 10 times per day with a period of 20–60 s each cycle. A dilute fertilizer solution is applied through the mist system.

FIGURE 5.52 Seeds placed in trays. Left tray is 1 d after a 20-h soaking period plus 24-h drying. Right tray is after soaking and drying (From V. Enrique Valdivia Benavides, Peru. With permission.)

FIGURE 5.53 Production room with mist. (From V. Enrique Valdivia Benavides, Peru. With permission.)

Production achieved by this method averages about 1:5 times by weight. This may be increased as high as 1:12 with the use of good seed. A general production ratio of 1:8 is expected in alfalfa or bean sprout systems. This operation uses wheat, barley, and corn as the seed sources. The animals consume all of the plant matter including roots, seeds, and foliage (Figures 5.54 and 5.55).

The operation claims that with a daily rationing of 12 kg of grass per day for dairy cows they have achieved a greater than 7% increase in milk production in cows producing more than 28 L of milk per day and a 53% increase in cows producing 14 L or less daily. In pregnant cows abortions were reduced to near zero. Cows also stayed dry for less time after bearing calves. Beef cattle gained 1.4 kg/d when fed 7–8 kg of green fodder plus 7 kg of concentrate.

HydroGreen Inc., a division of local chain ag-tech company CubicFarms Systems Corp., with headquarters in Langely, British Columbia, Canada, has developed an automated livestock feed growing-technology. The "HydroGreen Grow System" – is an automated indoor growing system to produce livestock feed year-round, in any climate, from seed to feed in six days. It performs all growing functions automatically including seeding, watering, lighting, harvesting, and re-seeding, as well as cleaning. The HydroGreen Grow System is available in a range of sizes and is scalable with multiple modules.

A touch screen controller shows each stage of the six-section module to enable adjustments for seeding, watering, lighting, and harvesting (Figure 5.56). The growing system consists of six to eight vertically stacked moveable conveyor growing shelves. The growing cycle begins with the sowing of the seed using an automated seeder that delivers an even depth of seed onto the shelf film

FIGURE 5.54 Finished corn ready for animal consumption. (From V. Enrique Valdivia Benavides, Peru. With permission.)

FIGURE 5.55 Finished barley. (From V. Enrique Valdivia Benavides, Peru. With permission.)

until the shelf is fully seeded. The seed depth may be adjusted for individual crop requirements. Once the shelf is fully seeded, automatic overhead sprinklers water until the seed is fully moistened. Watering continues with the sprinkler and a drip irrigation system that feed and cool the roots of the seedlings through sprouting and subsequent development (Figure 5.57). LED lighting above each shelf provides optimum lighting for plant growth. It takes 6 d from seed to harvest, therefore, with a six-shelf system; one shelf is harvested each day (Figure 5.58). One pound of seed produces about five pounds of feed. According to HydroGreen, a 2,700 ft^2 (250 m^2) facility will yield 5 tons of fresh

FIGURE 5.56 Touch screen controller to operate each stage of the growing system on six-shelf growing module. (From CubicFarms, Langley, BC, Canada. With permission.)

FIGURE 5.57 Automatic sprinkler watering system above each shelf. (From CubicFarms, Langley, BC, Canada. With permission.)

FIGURE 5.58 HydroGreen Growing System with eight tiers. (From CubicFarms, Langely, BC, Canada. With permission.)

livestock feed per day. Larger production centers combining multiple growing systems could yield upwards of 140 tons of fresh livestock feed per day.

During harvesting, the shelf of fresh livestock feed moves to the front of the HydroGreen Grow System (Figure 5.59), where the crop is cut into strips that drop onto a conveyor belt (Figure 5.60) that transports the product out of the growing room and onto a feed wagon that then transports the green fodder to the livestock location. The grow belt is automatically cleaned as it rotates back and is automatically seeded again to repeat the cycle (Figure 5.61).

5.5 ALFALFA AND BEAN SPROUTS

Sprouts of alfalfa, beans, radish, broccoli, and mixtures of alfalfa with onions, garlic, clover, cabbage, fennel, leek, lentil, cow peas, and green peas are popular for human consumption in salads, sandwiches, and oriental cooking. Most alfalfa blends are made up of from 60–80% alfalfa with the remaining part one or more of the others.

5.5.1 Alfalfa Culture

Raw seed must be surface sterilized to kill fungi and bacteria. Of particular concern is possible contamination by *Salmonella*, which can be killed by 2,000–4,000 ppm active chlorine for at least 10 min. The author has used a concentration of 2,000 ppm for up to 30 min without any reduction in seed viability.

Seeds are rinsed in plastic bins with raw water several times until all dirt is removed before sterilization. Rinse the seed until the drain water is clear, then surface sterilize the seed. One part bleach to 19 parts raw water will give a 3,000-ppm chlorine solution. Rinse the seed several times after surface sterilizing until the water drains clear.

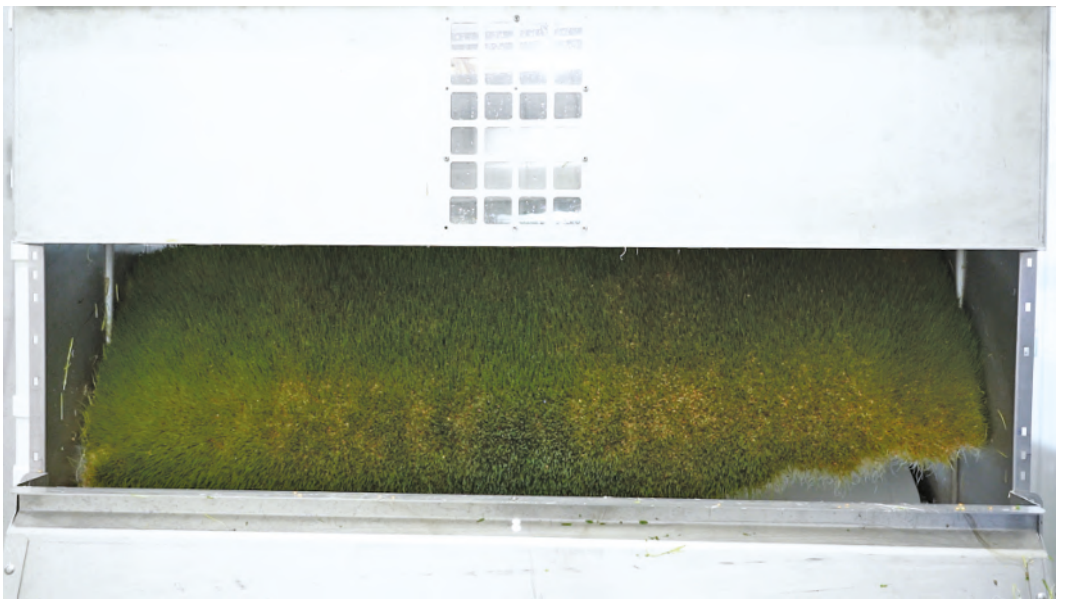

FIGURE 5.59 A HydroGreen Grow System with a view of the harvesting end. (From CubicFarms, Langely, BC, Canada. With permission.)

FIGURE 5.60 The fresh green feed is automatically cut into strips at harvest and then is transported out of the grow room by a conveyor belt. (From CubicFarms, Langely, BC, Canada. With permission.)

FIGURE 5.61 Automatic seeding of the shelf after harvesting. (From CubicFarms, Langely, BC, Canada. With permission.)

Spread the seed 5-cm (2-in.) thick in plastic trays or bins and soak for 4–6 h to imbibe. Change the water every hour to aerate. All water used in these processes should be chlorinated before filtering with sand and activated charcoal. It is convenient to store the clean water in plastic tanks having covers and connecting them using pipes to a closed system pressurized by a pump. Of course, all containers, trays, and so on must be sterilized with a 10% bleach solution before use. Water temperature must be maintained at 21°C (70°F) by the use of a boiler before entering the growing facilities. Seeds must swell but not break their seed coats. Wash them several times again before placing them in the growing trays.

The two most common types of growing systems are racks and rotary drums (Figure 5.62). Stainless steel racks may be single or double (Figure 5.63) mounted on casters to facilitate their movement. Single racks are 61 cm (24 in.) wide by 1.4 m (56 in.) long and 2 m (80 in.) high. Racks may contain 7–10 shelves depending on the crop. With alfalfa, use the 10-shelf rack.

Growing trays are of high-impact rubber-modified polystyrene (Figure 5.64). Ribbing maximizes drainage and minimizes root compaction. Ten-level single racks hold 20–30 trays, whereas double racks with eight levels hold 48 trays. Set up sufficient racks in a growing room to meet market demand.

Elaborate commercial systems use a computerized automatic water car that travels between the rows of racks. Less sophisticated fixed mist nozzles mounted above each level of the rack will perform the same task. Three trays per rack level may be watered by two mist nozzles located equidistant above each level (Figure 5.65).

An irrigation controller with solenoid valves automatically irrigates the sprouts at set intervals. Alfalfa sprouts are greened by passing the rack(s) through a light room for a few hours to a day depending on the amount of greening required by the market.

The growing cycle is between four and five days. The seeds may be sprouted in bulk trays or placed in clamshell plastic containers. Bulk trays hold about 1 lb or 0.5 kg of imbibed seed or 20 clamshells. Spread 0.25–0.5 in. (0.6–1.25 cm) of seed in the trays. Set the irrigation cycles at 30 s/h or 1 min/2 h. Within four days the sprouts will grow about 2.5 in. or 6 cm in height (Figure 5.65). Rinse the sprouts in cold water at 36–37.5°F (2–3°C) as soon as they are harvested.

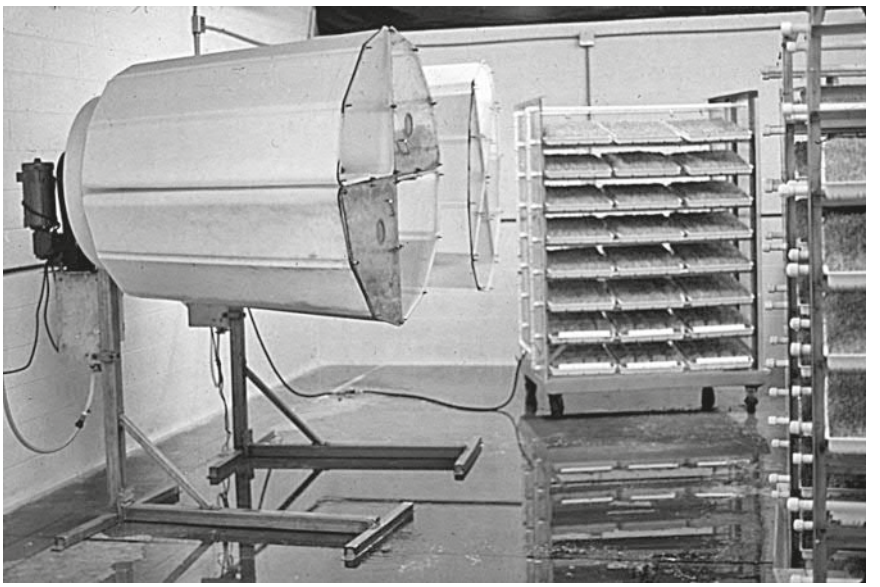

FIGURE 5.62 Alfalfa sprout growing systems of racks and rotary drums.

FIGURE 5.63 Stainless steel racks on casters.

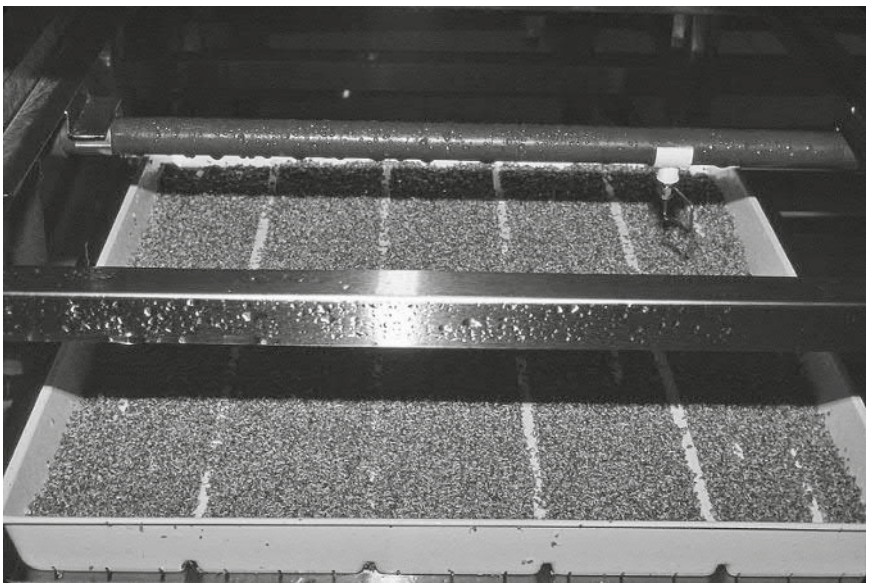

FIGURE 5.64 Mist nozzles above growing trays. Sprouts are 1 d after soaking. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 5.65 Alfalfa sprouts ready to harvest after 4 d. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

At all times during production and harvest, handle sprouts with strict sanitation procedures using gloves, smocks, and hair caps. During the washing process immediately after harvesting at least 60% of the seed coats should be removed. This will usually occur as the sprouts are gently agitated during the washing process. Sprouts are then spin dried in a centrifuge before packing so they will have a shelf life of at least five days.

When growing the sprouts in clamshell trays, wash them after the second day when they reach about 1in. (2–3 cm) in height; then place the same amount of sprouts in the 20 clamshells that would fill the trays. Grow them on for another 2–3 d. All equipment including trays and washing bins, must be sterilized with a 10% bleach solution immediately after use.

A fully automated rotary drum system washes, soaks, presprouts, and grows the seed (Figure 5.62). The drum is divided into four quadrants or growing chambers. Temperature, ventilation, water flow, rotation speed, and light may be programmed for a specific crop. During growth, the drum rotates once per hour and waters every six min.

With each quadrant containing 11.25 lb (5 kg) of seed, or 45 lb (20.5 kg) per drum, production will reach 350–450 lb (160–205 kg) of alfalfa sprouts in about 4 d. The alfalfa sprouts should weight from 8 to 10 times that of the seeds. A rack system housing 30 trays will produce 330 lbs. (150 kg) of bulk sprouts or 900 clamshells per growing cycle of 4–6 d. This assumes that each tray sown with 1 lb (0.5 kg) of seed will produce 11 lb (5 kg) of bulk sprouts. This is equivalent to 30 clamshells containing 4 oz (115 g).

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5.5.2 Mung Bean Culture

Preparation of the seeds before placing them in the growth room is similar to that of alfalfa. The soaking time varies from 4 to 6 h at 72°F (22°C), depending on seed age, quality, and source. Like alfalfa, the seed must imbibe but not break the seed coat before transferring to the growing chambers. The growth room temperature must be maintained between 72°F and 75°F (22–24°C). Large commercial bins mounted on stainless steel frames measure 37 in. (95 cm) x 40 in. (1.0 m) x 67 in. (1.7 m) high. They are constructed of corrugated plastic sides with removable slatted bottoms, which provide rapid drainage without the seed passing through. This system is automatically irrigated with a traveling boom irrigator that applies an even water flow over the seeds. The water cycles may be set at from 0 to 6 passes every 2 h. Numerous manufacturers offer a basic system of five bins with the computer-controlled overhead irrigator.

In Venezuela, at Hidroponias Venezolanas, we constructed smaller bins from plastic tubs used in the laundry industry. They are 24 in. x 24 in. x 22 in. high (60 cm x 60 cm x 55 cm high). They are supported on stainless steel frames having casters to facilitate moving them from the growing area to the packing facilities. The water was dispersed by use of two showerhead breakers mounted above each bin and a perforated plastic top as shown in Figure 5.66. A perforated false bottom provided drainage. Irrigation cycles are regulated by the use of a controller and solenoid valve in the header line for the showerheads mounted above the bins. During irrigation cycles ventilation fans are activated to exchange the air in the growing room.

The addition of dilute phosphorus and potassium nutrients during the second and third days of the growth cycle produces thicker sprouts.

Within 4–5 d, the sprouts are about 2.5 in. (6–7 cm) in length from the tip of the radical to the epicotyls (Figure 5.67). As the sprouts grow, the entire bin of sprouts should rise evenly. If low spots develop, there may be a lack of water, temperature increase, or insufficient oxygen.

FIGURE 5.66 Mung bean sprout bins. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 5.67 Mung beans harvested at 4–5 d. (From Hidroponias Venezolanas, Caracas, Venezuela. With permission.)

Seed coats must be removed during the washing process after harvesting. Float the sprouts in an ice water bath, slightly agitating the water while skimming the sprouts from the surface with a strainer. Care must be taken in handling the sprouts to prevent contamination (Figure 5.67). Spin dry the sprouts with a centrifuge, package, and immediately refrigerate them at 36–37.5°F (2–3°C). A commercial washing system that cools, washes, removes seed coats, and partially dries the sprouts is available. Bacteria are controlled with a chlorine injection system within the washer.

Similar to alfalfa, mung beans should produce 8–10 times their weight in sprouts. To achieve this production, it is important to purchase high-quality seed with high viability. It should be uniform in size and free of contaminants. Each seed source and batch should be tested before ordering a large amount. Bean sprouts suffer more than alfalfa from physiological disorders and diseases. Poor oxygenation, ventilation, or high temperatures result in poor germination and uneven growth. Iron or excessive chlorine in the water produces brown roots. As with other agricultural crops successful management through constant monitoring and adjustment of environmental conditions determines productivity and quality.

5.6 MICROGREENS

Microgreens are very similar to sprouts, the difference being that they are grown in the light, not darkness. They, like sprouts, can be grown on a small scale as a hobby at home or as small or large commercial operations.

Typical microgreens often include mixes of crops, Asian greens, tangy or mild mesclun mixes, radishes, and so on. To view the diversity of plants that can be used, one can view common garden seed catalogs such as Johnny's Selected Seeds (www.Johnnyseeds.com). Some common seeds include red amaranth, arugula, beets, borage, cabbages, chards, cress, kales, Mizuna, mustards, Pac Choi, purslanes, radishes, Shiso, sorrel, Tatsoi, and others.

Microgreens may be grown at home by following the simple procedure set forth here. Materials needed include plastic trays without holes, thick paper towels, a hydroponic nutrient concentrate, seeds, several compact fluorescent lights, and some bleach to sterilize the seeds. Johnny's Seeds defines a "Micro mix" as "gourmet vegetable confetti made from a variety of crops harvested at the seedling stage."

Purchase seeds specifically listed for use as microgreens as they are not treated with fungicides. Since they are not treated, they may have fungal spores and/or bacterial spores on their surface. These pathogens must be eliminated by surface sterilization to prevent them from causing death of the germinating seedlings. If different seedlings need to be combined in the same tray, select varieties having the same growth rate. Do not combine seeds that germinate quickly with those that germinate slowly. For example, radish is ready to harvest in 5–6 d, whereas some lettuce and other greens may take 7–10 d. Some useful combinations include purple and Diakon radishes, amaranth and all greens (Figure 5.68), amaranth and mild mesclun or mizuna, amaranth and spicy mesclun or spicy greens, and Komatsuna (green or red) with wildfire lettuce.

Surface sterilization of the seeds before placing them on the paper towels or capillary matting is critical to success. Use a 10% bleach solution (1 part bleach to 9 parts water) in a plastic cup to swirl the seeds around for 3–4 min; then rinse with raw water using a household strainer (Figure 5.69). Moisten the paper towels or mat with some raw water and then place the seeds from the strainer into the tray with a spoon and spread evenly around the surface using the spoon or clean fingers (Figure 5.70). When adding raw water for the first 3 d until the seed germinates, be careful to pour the water slowly along the edge of one end of the tray so that the seeds do not float.

Keep the sown tray under two compact fluorescent lights of about 30 W. The lights should be about 12 in. (30 cm) above the tray. Operate the lights for 12–14 h/d using a simple household time clock. After germination and the seeds have grown into the paper towels or mat (usually 3 d), start using a dilute nutrient solution (half the normal recommended strength). Nutrient concentrates can be purchased from hydroponic shops.

FIGURE 5.68 All greens and amaranth ready to eat at 7–10 d.

FIGURE 5.69 Surface sterilizing seeds with 10% bleach solution. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

Harvest the seedlings after 7–10 d using a pair of scissors to cut off the shoots as the roots are not consumed (Figure 5.71).

In general, commercial microgreen operations are not very large as the market demand is very limited. Usually a grower of other crops such as herbs and/or lettuce will set up a small area in his greenhouse for microgreen production. CropKing in Ohio (www.CropKing.com) builds systems for small commercial operations. They have two different sizes of microgreen packages, a two-rack

FIGURE 5.70 Spreading clean radish seed over capillary mat in tray.

FIGURE 5.71 Trays are 2 d and 9 d from sowing. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

system that fits in 18 ft x 28 ft (5.5 m x 8.5 m) of a greenhouse that is capable of producing 50 lb/wk (23 kg/wk) and a four-rack system that requires 22 ft x 56 ft (6.7 m x 17 m) that should produce 100 lb/wk (46 kg/wk).

Their basic one-rack system consists of 24 PVC growing channels on a galvanized steel frame housing 4 channels on each of 6 levels with the plumbing system delivering nutrient solution to each growing channel (Figure 5.72). Each rack is 14 ft (4.27 m) long by 44 in. (1.1 m) wide by 6 ft 4 in. (1.9 m) high. A submersible pump in a tank below circulates the solution to the trays, and the solution returns to the tank or cistern (Figure 5.73). This system can easily be part of an NFT lettuce or herb system using the same tank, pump, chiller, and so on.

The microgreens are seeded on a capillary mat; or in the case of CropKing's system they use burlap mats (Figure 5.74). The mats hold the seeds in place so they will not wash away on irrigation. The mats are needed to distribute the nutrient solution and retain moisture between irrigation cycles.

The irrigation system is a closed system, with the solution entering via drip lines on one end and collected by return pipes to the cistern (Figures 5.72 and 5.73). Valves at each channel permit adjustment of flow to each channel. The channels are sloped to the drain ends, similar to an NFT system. A typical system growing microgreens is shown in Figures 5.75 and 5.76.

Crops are ready to harvest from 7 to 14 d, depending on the growth rate of the particular species. The burlap mat is removed from the growing channels with the plants attached and hung to "drip dry" for a short time. Then the mat is moved to a supporting area where they hang over a tub that collects the product as it is cut with an electric knife (Figure 5.77). They are then placed in clamshell containers and packaged for delivery. This is a different approach from Koppert Cress B.V. that grows the microgreens within the clamshells.

One of the largest growers of microgreens is Koppert Cress B.V. with greenhouse operations in Holland and other European countries as well as in North America. They grow in an ebb and flood system (Chapter 6). They focus on the restaurant trade worldwide, but also sell products in clam shell (rigid plastic) containers (similar to sprouts) to the retail supermarket trade (Figure 5.78) and in sleeved plastic containers without lids (Figure 5.79). They sow the seeds in a clean medium of natural fibers (Figures 5.80 and 5.81). Products are food safe and can be used as is without washing.

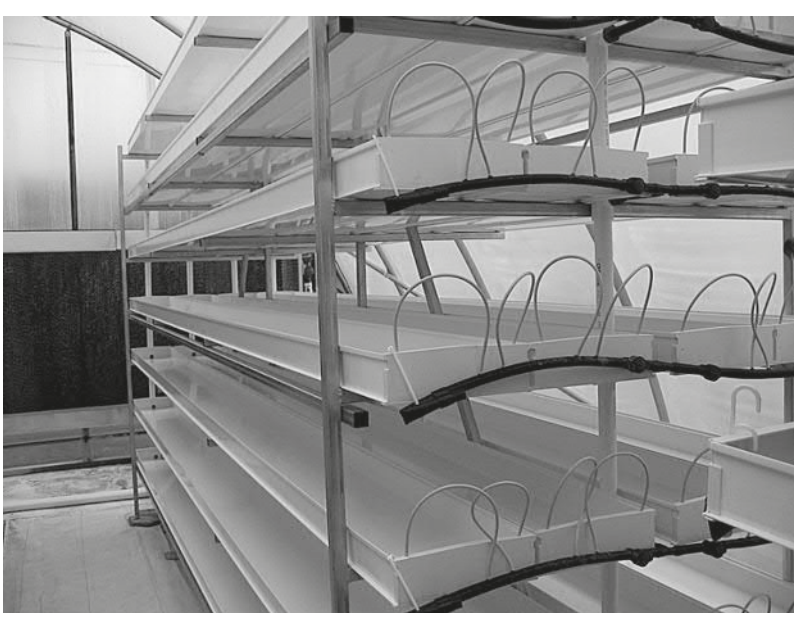

FIGURE 5.72 A basic one-rack microgreen system. (From CropKing, Inc. Lodi, OH. With permission.)

FIGURE 5.73 The basic one-rack microgreen system showing the drain ends. (From CropKing, Inc., Lodi, OH. With permission.)

FIGURE 5.74 Microgreens germinating on burlap mat. (From CropKing, Inc., Lodi, OH. With permission.)

FIGURE 5.75 Microgreens growing in channel on the rack showing the inlet drip line. (From CropKing, Inc., Lodi, OH. With permission.)

FIGURE 5.76 Microgreens growing in the rack system. (From CropKing, Inc., Lodi, OH. With permission.)

FIGURE 5.77 Microgreens "drip drying" before harvesting. (From CropKing, Inc., Lodi, OH. With permission.)

FIGURE 5.78 Sakura cress microgreens in a clam shell container.

FIGURE 5.79 Mustard and borage cress microgreens.

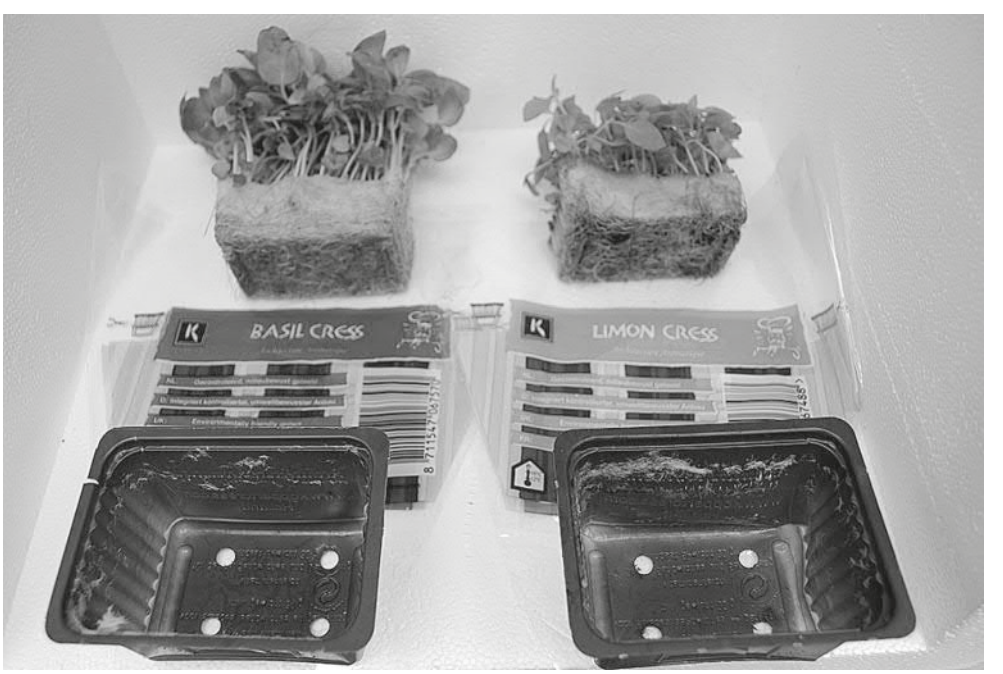

FIGURE 5.80 Sweet and lemon basil cress.

FIGURE 5.81 Italian sweet basil microgreens growing in natural fiber.

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6 Nutrient Film Technique

6.1 INTRODUCTION

The Nutrient Film Technique (NFT) is a water-cultural technique in which plants are grown with their roots contained in a plastic film trough or rigid channel through which nutrient solution is continuously circulated.

Work on NFT cropping was pioneered by Allen Cooper at the Glasshouse Crops research Institute in Little Hampton, England, in 1965. He continued with modifications of the NFT system and wrote reviews during the 1970s and 1980s (Cooper, 1973, 1985, 1987a, 1987b). The term *nutrient film technique* was coined at the Glasshouse Crops Research Institute to stress that the depth of liquid flowing past the roots of the plants should be very shallow in order to ensure that sufficient oxygen would be supplied to the plant roots. Other workers (Schippers, 1977) call it *nutrient flow technique* since the nutrient solution is continuously circulated.

6.2 EARLY NFT SYSTEM

In the earliest NFT system, a catchment trench was dug across the middle of the greenhouse floor and the ground sloped on either side toward this trench. A minimum slope of 1% to a maximum of 4% was tested. The steeper slopes reduced the effect of localized depressions. The trench was lined with either vinyl or polyethylene film. "Layflat" polyethylene troughs were placed on strips of board 8 in. (20 cm) wide at the normal spacing of plant rows sloping toward the central catchment trench from each side (Figure 6.1). Holes were punched in the layflat film at centers suitable for the specific crop to be grown. The lower end of each trough hung down into the catchment trench, while the upper end of each line was turned upward and over and sealed with PVC tape to prevent the loss of nutrient solution.

Nutrient solution in the catchment trench was circulated to the upper ends of each layflat by a submersible pump and ABS plastic piping. Gate valves installed at the inlets to each layflat line regulated the flow of nutrient solution evenly into each trough. The roots of the plants were inserted into the layflat through the planting holes, and the upper parts of the plants were supported in the normal way by tie strings suspended from support cables in the greenhouse.

6.3 LATER NFT SYSTEMS

The NFT system went through lots of modifications in an attempt to resolve oxygen deficit and ethylene buildup problems in plant roots. Plants were sown and grown to transplants in peat pots, peat pellets, or rockwool cubes and then placed on a narrow polyethylene sheet in each plant position in the row. The edges of the polyethylene were turned up and around the sides of these growing pots or cubes and stapled between every other pot (or cube) to form a gully through which a thin stream of nutrient solution flowed.

While this configuration (Figure 6.1) permitted better ventilation of air within the gully and reduced ethylene buildup, it still was not the solution for many longer-term vine crops such as tomatoes, cucumbers, and peppers. The roots of these crops quickly grow through the pots (or cubes) and spread out in the shallow stream of nutrient solution flowing down the gullies. They merge to form a single, thick, continuous mat in the bottom of the gullies, which eventually blocks the flow of solution and cause the solution to rise within the gullies, reducing oxygenation to the roots.

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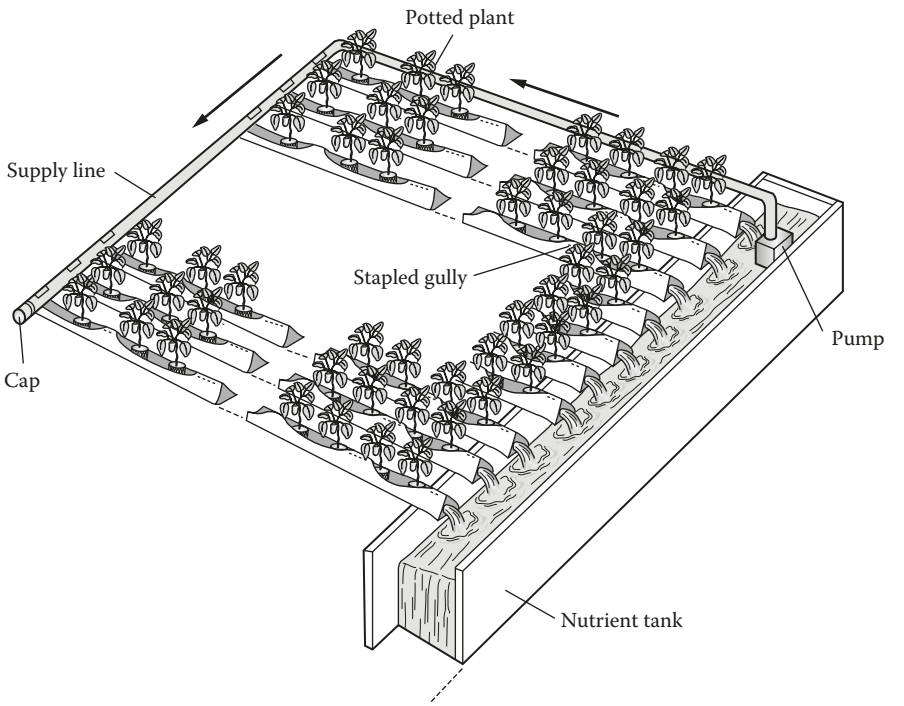

FIGURE 6.1 Layout of a series of NFT gullies and solution tank. (Adapted from Cooper, A.J., *The Grower*, 79, 1048–1052, 1973. With permission. Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

6.4 COMMERCIAL NFT SYSTEMS

In the early 1990s large commercial operations growing tomatoes were attempted in over 68 countries. However, these oxygen deficit problems continued, with the exception of the growing of low-profile, short-term crops such as lettuce and some herbs. Rockwool was introduced in the 1990s and it soon became the most accepted method of growing vine crops such as tomatoes, peppers, and cucumbers. Today, the NFT system is used principally for lettuce and herbs.

A layout of an NFT system is shown in Figure 6.2. Nutrient solution is pumped through a main PVC pipe to headers that are located at the high ends of the NFT channels. The solution is discharged from the headers into the gullies or channels through small flexible drip lines. The solution flows by gravity down the channels and is drained at the lower end to a large catchment pipe, which conducts the solution back to the cistern. Such channels for growing low-profile crops are located on benches to facilitate caring of the plants. This is discussed later in this chapter in Section 6.6.

Some growers have developed a modified rockwool-NFT system in which they grow the plants in partial slabs of rockwool placed in NFT channels. This system grew vine crops without any lack of oxygen. But, it is more complicated and still does not provide as much oxygenation to the plant roots as a complete rockwool setup. For further information on NFT systems refer to Edwards (1985), Burrage (1992), Goldman (1993), and Gilbert (1996).

6.5 NUTRIENT FLOW TECHNIQUE: VERTICAL PIPES, A-FRAME, OR CASCADE SYSTEMS

In 1977, Dr. P.A. Schippers developed what he termed the *nutrient flow technique* at the Long Island Horticultural Research Laboratory of Cornell University at Riverhead, New York. He modified the

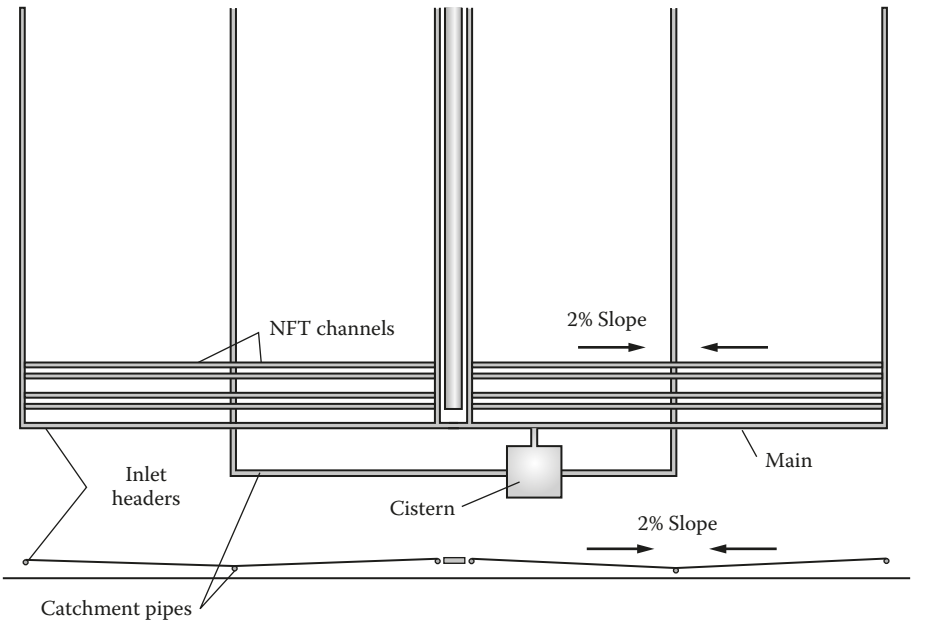

FIGURE 6.2 Layout of an NFT system. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

NFT system in an effort to save greenhouse space. By increasing the number of plants that can be grown in a given area of greenhouse, the cost per plant can be reduced. Experimental work was performed with lettuce in vertical pipes, down which the nutrient solution dripped, moistening and feeding the plants. Such a system is demonstrated at Epcot at the Walt Disney World Resort near Orlando, Florida as shown in Figures 5.49 and 5.50.

A nutrient solution is sprayed into the vertical pipes traveling on a conveyor system. As the pipes carrying the plants pass the point where nutrients are sprayed onto their roots within the pipe, they travel above a nutrient collector reservoir; thus the immediate drainage flows back into the system.

This system is used to grow lettuce, herbs, strawberries, and squash. The best prospect for this system is for crops that are harvested over a longer period, such as strawberries, peas, beans, and so on.

Schippers pursued different ways to increase the use of vertical space in the greenhouse by use of the NFT, particularly for low-growing crops such as lettuce (Schippers, 1980). He built what he termed the *cascade system*. Growing troughs of 3-in. (7.6-cm)-diameter PVC plastic pipe were cut open and suspended one above the other up to eight toughs high. The nutrient solution entered the high end of the slightly sloping top pipe, exited at the low end of that pipe into the high end of the next one, and so on, to the reservoir from where it was pumped. The system was successful with lettuce, radish, peas, and other crops. This system, shown in Figure 6.3, is used for fairly small plants.

The system is more efficient in utilization of greenhouse space if the growing channels are mounted on A-frames. The A-frames must be oriented north–south in the northern latitudes so that shade from one side will not be cast on the other. The system is suitable only for low-profile plants such as lettuce, strawberries, spinach, and some herbs.

Several factors must be considered in the design of the A-frame system. The base of the frame must be wide enough to eliminate any mutual shading of one tier over the next lower one. The tiers of growing channels must be separated from each other with adequate distance to allow for the mature height of the crop grown. That is, the plants of a lower tier must not grow into those of the

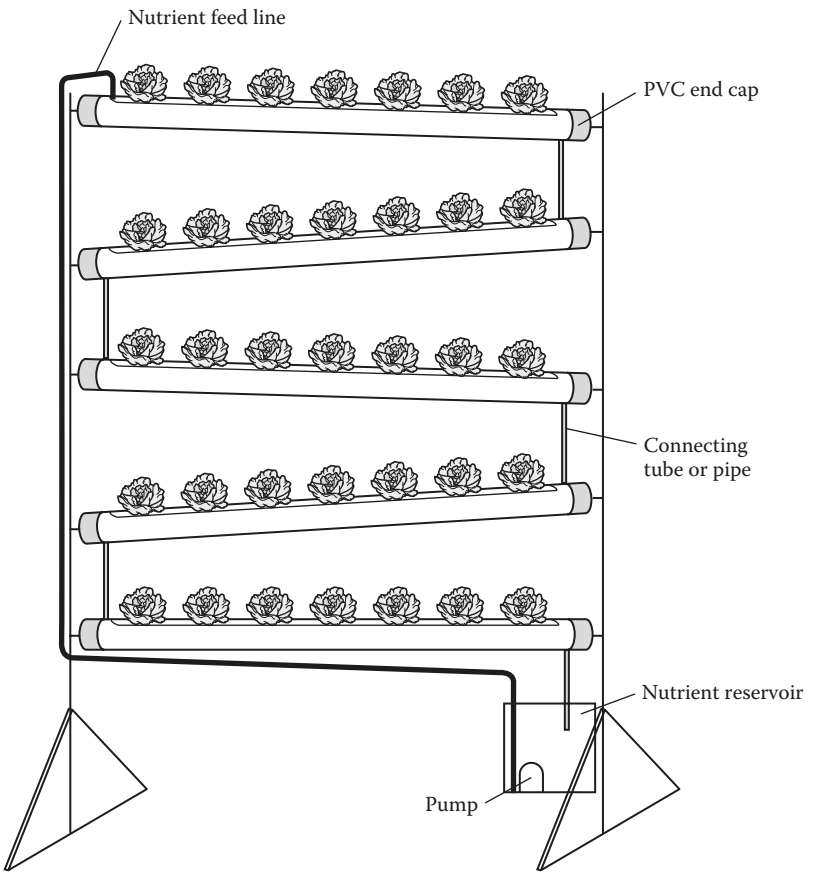

FIGURE 6.3 Details of a "cascade" NFT system. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

above tier. Finally, since this is basically an NFT system, all principles of oxygenation, nutrition, and optimum solution temperature apply. The total channel length for any combination of tiers should not exceed 30 m (100 ft) in order to provide sufficient oxygenation. The distance of the combination of tiers can be reduced by draining sections into a main return header to the cistern below. A minimum slope of 2% is necessary to provide adequate solution flow.

Plants may be sown in rockwool cubes (1.5 in. x 1.5 in. x 1.5 in.) and later placed in mesh pots that fit into the plant spaces of the NFT channels. A large root mat will form at the base of the pots and grow together.

While the productivity is greater, the capital cost of such a cascade system and the additional time required to clean each channel between crops does not make it economically feasible when almost the same plant density can be achieved using the floating (raft) system.

6.6 GUTTER AND PIPE NFT CHANNEL SYSTEMS

A gutter NFT system may be constructed of conventional plastic eaves troughs used for homes, or a system may be purchased from several manufacturers of a rigid PVC extruded growing channels, such as those available from American Hydroponics and CropKing (Appendix 2). This NFT channel is 4 in. (10 cm) wide by 1.5 in. deep (4 cm). Rehau Plastics, Inc. also makes a NFT gutter with

FIGURE 6.4 Benching system constructed for support of the NFT channels. Note: The channels placed on the bench in the back. Also, note that the benches are sloping toward the greenhouse sidewall posts and there are 3-in. PVC drain pipe risers for the catchment trench to drain to for return to the nutrient cistern. (From American Hydroponics, Arcata, CA. With permission.)

a slightly different configuration. NFT channels are also available in extruded aluminum and are fabricated on-site by companies such as Zwart Systems (Appendix 2). These NFT channels are particularly suited for the growing of lettuce and herbs. While some manufacturers of NFT gullies make wider and deeper channels for other crops, the author would not recommend growing crops other than low-profile ones such as lettuce, bok choy, and herbs. Long-term crops with larger root systems plug the gutters, causing lack of flow of the nutrient solution and a resultant lack of oxygen, leading to blossom-end rot on fruit and eventual death of the plant.

The channels are available in any length but should not exceed 50 ft (15 m), as insufficient oxygenation, blockage of channels by roots, and nutrient gradients may occur. Channels of 50 ft length would be awkward to handle during harvesting and cleaning.

The maximum practical length would be about 15 ft (4.6 m). The channels are supported on metal frame benching to be at about waist height for convenience of working with the plants (Figure 6.4). Channels are sloped at 2–3% away from a central aisle to a catchment channel (Figure 6.5). For example, in a 30-ft (9-m)-wide greenhouse, two sets of NFT gullies (two 13 ft or one 12 ft and one 14 ft long) (4 m, 3.6 m, 4.3 m) can be sloped away from a 4-ft (1.2-m) central aisle to the catchment channel at the sidewall of the greenhouse. Channels are ribbed on the bottom for central flow of the solution.

Channels should have covers to prevent light entering and thus avoiding algae growth inside (Figure 6.6). Most leafy plants such as lettuce are spaced at 8 in. (20 cm) within the channel, and channels spaced at 6–7 in. (15–18 cm) from center to center. Smaller herbs can be spaced 6 in. (15 cm) within the channels and 6 in. (15 cm) between channels. Basil and lettuce grow very well in a NFT system (Figure 6.7).

Plants are seeded in 1-in. rockwool cubes or Oasis cubes (stage 1) and after 10–18 d are transplanted to nursery channels (stage 2) (Figure 6.8). These nursery channels have plant holes at 2 in. (5 cm) within the gulley and are separated by 4 in. (10 cm) center to center.

This NFT system utilizes approximately 80% of the greenhouse floor area. In a 1-acre greenhouse with 30-ft (9.1-m)-wide ranges, allowing for central aisles of 4 ft (1.2 m), two sets of 13-ft beds (4 m) could be oriented perpendicularly to the gutters and posts of the greenhouse. The greenhouse with 12 ranges of 30 ft x 120 ft (9.1 m x 36.6 m) would contain, using 8 in. x 6 in. spacing of

FIGURE 6.5 Basil in NFT channels (ribbed) with drain ends of channels into open collection (catchment) gutter. (From American Hydroponics, Arcata, CA. With permission.)

FIGURE 6.6 Closed catchment gutter. Note: The drain line from the catchment trench to the main return below to the cistern. (From American Hydroponics, Arcata, CA. With permission.)

channels, 105,000 plants (8,800 plants per range). This assumes using two benches 13 ft x 110 ft of useable greenhouse floor area per range.

An example of a cropping sequence for lettuce is as follows:

(Note: This will vary for location, as it is dependent on sunlight and day length.)

1. Sow in 1-in. rockwool cubes in 200 pads per flat (1 ft x 2 ft trays) (30.5 cm x 62 cm).
2. Grow in these flats on a propagation bench for 18 d (stage 1).

FIGURE 6.7 Basil growing in NFT system. Note: The inlet tubes, header and risers with valves from main below at floor level. (From American Hydroponics, Arcata, CA. With permission.)

FIGURE 6.8 Numerous varieties of lettuce. Note: The four nursery channels on the right side. (From American Hydroponics, Arcata, CA. With permission.)

FIGURE 6.9 Removal of entire NFT channel from growing table to allow easy harvesting. (From Gourmet Hydroponics, Inc., Lake Wales, FL. With permission.)

3. Transplant to nursery channels at 18 d (stage 2).
4. Grow for 10–12 d (28–30 d from sowing) in nursery channels.
5. Transplant finally to growing (finishing) channels at 28–30 d from sowing (stage 3).
6. Grow for 20–25 d (25 d gives 14 crops per year) in growing channels.

Total days from sowing to harvest: 18 + 12 + 25 = 55 d. The reason for using the nursery channels is to make more efficient use of the bench area, as the final growing stage 3 will be less time than if the plants were placed in the finishing channels after stage 1.

To harvest, the channels are removed with the plants intact (Figure 6.9). This allows the grower to select the more advanced plants to harvest earlier than smaller heads of the same age, should this occur during unfavorable weather conditions. After selectively harvesting, the channels may be replaced in their original position to allow the remaining lettuce to continue growing until they reach harvestable weight. However, on a large-scale operation, this is not possible, as the cropping cycle would be interrupted. Plants are cut off at the crown with a sharp knife. In some cases, the plants may be packaged in clamshell containers so the roots are pruned back, but still intact in the growing cube to keep the product fresh in the market.

Any dead or yellowing leaves at the base of the plants are removed before moving them to the packing area. The channels are transported to a central cleaning and sterilizing vat where they are rinsed with clean water followed by soaking in a 10% bleach solution for at least 1 h. The trays should be rinsed with water upon removing from sterilization and allowed to dry.

Lettuce is packed in polyethylene bags and placed in cardboard boxes for shipping. It must be refrigerated at 35°F (1.7°C). The shelf life for Bibb lettuce is 7–10 d.

In many countries, including Brazil, the NFT system of growing lettuce, herbs, and particularly arugula has become popular, resulting in a rapidly expanding hydroponic industry. Often it starts out as experimental work in a university and then gets applied on a commercial scale. In Florianopolis, Brazil, Universidade Federal de Santa Catarina conducts research into NFT growing of herbs, lettuce, and arugula (Figures 6.10 through 6.12).

FIGURE 6.10 Arugula (Roquette) in NFT channel. Note: The plants are sown in a type of "Oasis" cube. Also, two cubes with about 10 seedlings are set into each planting hole of the NFT channel. (From Universidade Federal de Santa Catarina, Florianopolis, Brazil. With permission.)

They are experimenting with coating the surface of the NFT channels with an aluminum foil tape to reflect heat from the gullies in an effort to maintain lower temperatures of the nutrient solution. Once an industry develops growing these crops with NFT, companies manufacture NFT channels and other hydroponic supplies and components, such as greenhouses, irrigation equipment, nutrients, substrates, and pest and disease control products. For example, Dynacs in Sao Paulo, Brazil, manufactures NFT channels of numerous dimensions.

Harvested arugula is often sold in sleeve packages with two bunches of arugula as shown in Figure 6.13. The roots and cubes are kept on the bunches.

6.7 HORTIPLAN AUTOMATED NFT SYSTEM

Hortiplan N.V., near Mechelen, Belgium (www.hortiplan.com/MGS), has designed and installed fully automated NFT systems. Belgium has over 600 ha (1,500 acres) of greenhouse lettuce production. Of the 600 ha, 500 ha are in greenhouses without central heating, so are termed *cold frames*. The other 100 ha are heated greenhouses. Most of these producers grow in soil. A number of operations in Belgium and Holland have converted their soil-growing lettuce operations to the automated "mobile gully system" (MGS) of Hortiplan. They have also installed MGS in Australia,

FIGURE 6.11 Lettuce in NFT channels coated with reflective foil tape to reduce root temperatures. (From Universidade Federal de Santa Catarina, Florianopolis, Brazil. With permission.)

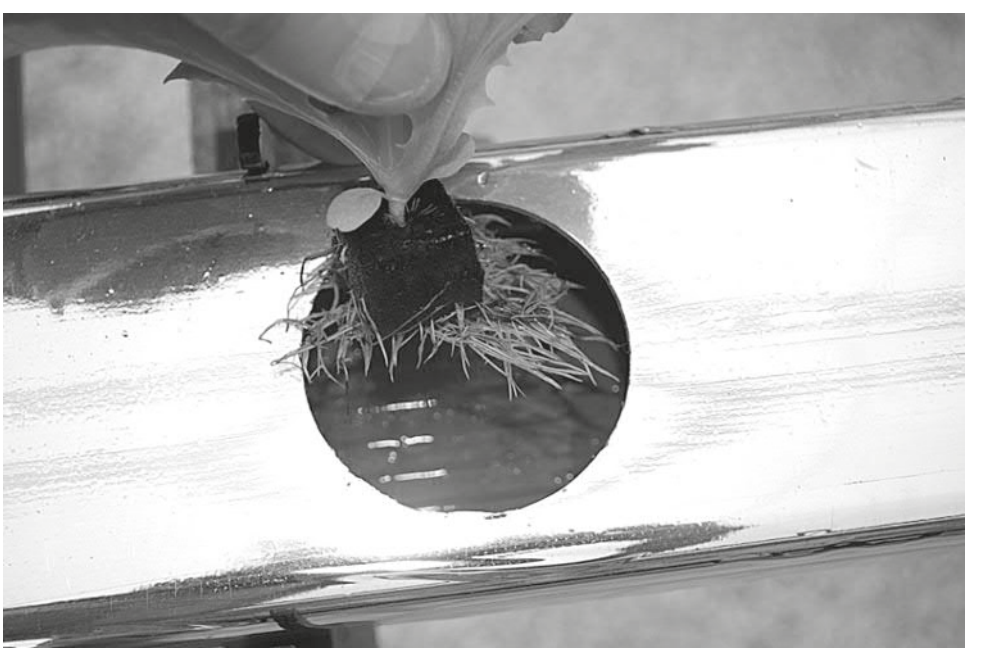

FIGURE 6.12 Young lettuce seedling rooting well into the NFT channel. Note: The healthy roots spreading out from the growing cube. Also, notice the ridges in the bottom of the NFT channel, which directs the flow of the nutrient solution under the plants. (From Universidade Federal de Santa Catarina, Florianopolis, Brazil. With permission.)

FIGURE 6.13 Arugula marketed in sleeved packages containing two bunches. (From Hidroponia Mandala, Brazil. With permission.)

Italy, the United Kingdom, and Latvia. One company in the United States, Holandia Greenhouses, Carpenteria, California, has 7.2 ha (18 acres) of lettuce and herbs growing using the MGS. In 2017 Hortiplan installed a MGS in Lufa Farm's Anjou facility of 63,000 ft^2 (5,853 m^2) in Montreal, Quebec, Canada (see Chapter 15 for more information on Lufa Farms).

The seedlings are either grown in a special nursery room separate from the automated production area, or in countries that have a large concentration of lettuce growers; this seedling production can be contracted to a specialized nursery company. Sowing is into large peat cubes at a density of 300/m^2 (Figure 6.14). They are grown 3–4 wk before entering the automated production area.

The plants then enter the first part of MGS, the extended nursery. This extended nursery is especially advantageous for growers producing heavy lettuce (large heads). About 7% of the surface area contains more than 32% of the total number of plants in the greenhouse. They are removed and placed in special trays of 100 seedlings/square meter (Figures 6.15 and 6.16) where they can grow under very high density. The peat blocks are spaced 5 cm x 5 cm (2 in. x 2 in.) in the summer and 6 cm x 6 cm (2.3 in. x 2.3 in.) in winter (October–March). In winter, the larger blocks are used, as they need fewer irrigation cycles, thus reducing humidity and possible fungal infection. The extended nursery is generally an area at the front of the greenhouses near the growing gullies. These trays move along a bench from the side where they are transplanted to the other side near the NFT gullies. After 10–14 d in winter or after 7 d in summer they are transplanted to the NFT channels (gullies) (Figure 6.17). Transplanting can be done manually or by a plant robot (Figures 6.18 and 6.19).

When the gullies are transplanted, they automatically move on a conveyor underneath the benching to the far end of the benches (Figure 6.20). There they are raised up and set up on top of the bench (Figure 6.21). The original spacing of the gullies is 40 plants per square meter.

They are automatically separated over the 5- to 6-wk growing period by a draw bar system underneath (Figure 6.22). While moving along the growing field (bench) the space between the gullies widens through 4–5 spacings as the plants grow, to provide optimum space for the plants in each stage of growth over the 5- to 6-wk period in summer and 8- to 11-wk period in winter

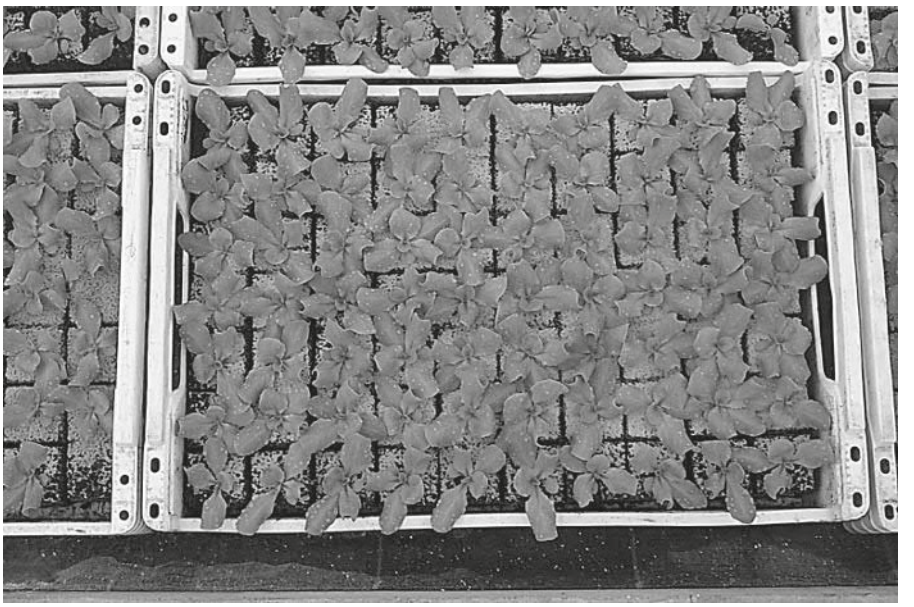

FIGURE 6.14 Lettuce seedlings 3–4 wk old ready to enter the extended nursery. (From Hortiplan N.V., Belgium. With permission.)

FIGURE 6.15 Lettuce seedlings arriving in nursery trays on left and transplanting to the extended nursery on the right. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.16 Transplanting lettuce seedlings to special nursery trays in the extended nursery. Note: The combination of red and green oakleaf lettuces in each block. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.17 Transplanting the seedlings from the extended nursery trays to the NFT growing channels. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.18 Automatic transplanting machine takes the seedlings and places them into the NFT growing channels. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.19 Plant robot transplanting to the NFT growing channels. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.20 Lettuce in gullies traveling underneath to far end of the growing bench. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.21 The gullies at the far end of the bench are lifted automatically to the top of the growing field (bench). (From Hortiplan, N.V., Belgium. With permission.)

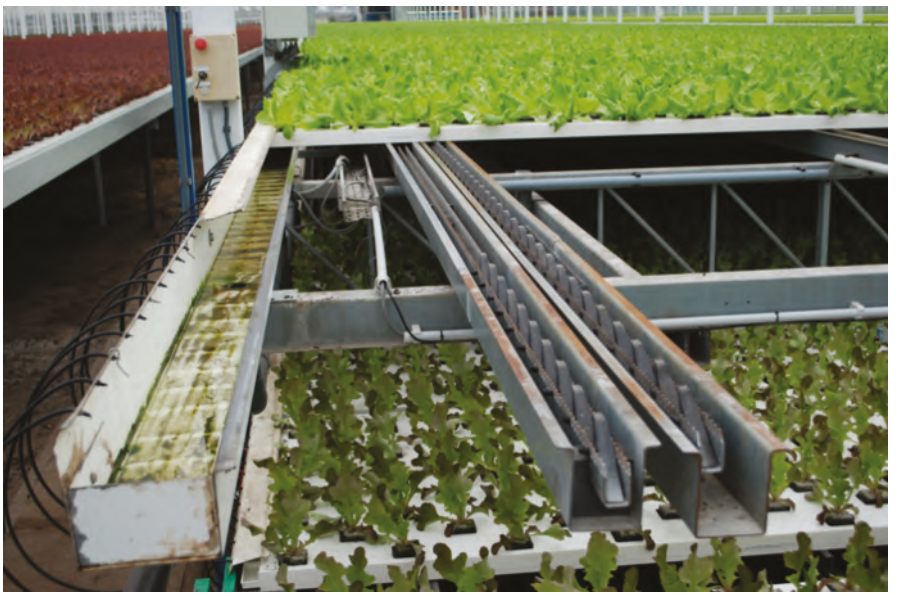

FIGURE 6.22 The drawbar to space the gullies. Note: The inlet lines on the left with the trench under them. The trench collects excess nutrient solution and drains it below to the main drain that returns the solution to central storage tanks where it is treated before re-circulation to the gullies. (From Hortiplan, N.V., Belgium. With permission.)

(Figures 6.23 and 6.24). They end up at a spacing of 14 plants per square meter (Figure 6.25) to get heads of 400 g (1 lb).

Lettuce gutters are 10 cm (4 in.) wide, and herb gullies are 7 cm (2.75 in.) wide. The length of the gutters depends on the width of the greenhouse bays: 9.6 m (31.5 ft), 12.0 m (39.4 ft) or 12.8 m (42 ft). The most common gutter lengths are the 12.0 and 12.8 m, as these are the most common house widths. Plant hole size is determined according to the crop and substrate size, such as peat block, rockwool, or others. The most common are 5 and 6 cm. The holes are square, with most common dimensions of 6.5 cm x 6.5 cm or 6.8 cm x 6.8 cm. The depth of the gutter is 5 cm, and holes are spaced within the gullies at 26 cm (10.2 in.) centers. The final spacing between gullies to get 14 plants per square meter is 24–25 cm. This spacing is for Belgium, where large lettuce of over 400 g (almost 1 lb) is grown. The density can be higher for smaller lettuce.

The gullies are irrigated by a trickle feed system. The gullies have open lips on one end to collect the nutrient solution. The trickle feed lines are located at intervals so that they will line up with the gullies as they move. This movement of gullies so that they always end up in front of a feed line is accomplished by draw bars. There is a collection trench immediately below to collect any solution that does not enter the gulley, when emptying the system if overproduction occurs or during maintenance (Figure 6.22). The position of the inlet lines may also be shifted on the cover of the trench. The inlet lines are connected to a main, and the drainage from the collection gutter is piped below, resting on top of the second inlet collection gutter (Figure 6.26). The main drains conduct the nutrient solution to the central part of the greenhouse where the water treatment and adjustment processes of the nutrient solution take place before recirculation (Figure 6.27). The lower collection gutter is part of the inlet system for the gullies as they move underneath the growing field to the far end of the greenhouse after transplanting.

There is a 1% slope in the gutters from the inlet to the discharge end. The solution returns to a tank where it is sterilized and stored as treated water, which is then mixed with the injection before

FIGURE 6.23 The gullies are initially spaced touching as they are placed onto the growing field. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.24 The gullies are progressively spaced as they grow to a final spacing of 14 plants per square meter. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.25 Final spacing with Lollo Rossa lettuce and fennel. This is the catchment trench end of the gullies where the solution is collected and returned via the treatment system. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.26 The inlet-catchment trench. Note: The inlet header, trickle feed lines, and return drain main on top of the lower inlet-catchment trench that feeds and drains the gullies as they move from one end of the bench to the other underneath the growing field. Note: The drain end of the channels on the right of the pathway that collects the solution at the return end. Lollo Rossa lettuce on the right and Bibb lettuce on the left benches. (From Hortiplan, N.V., Belgium. With permission.)

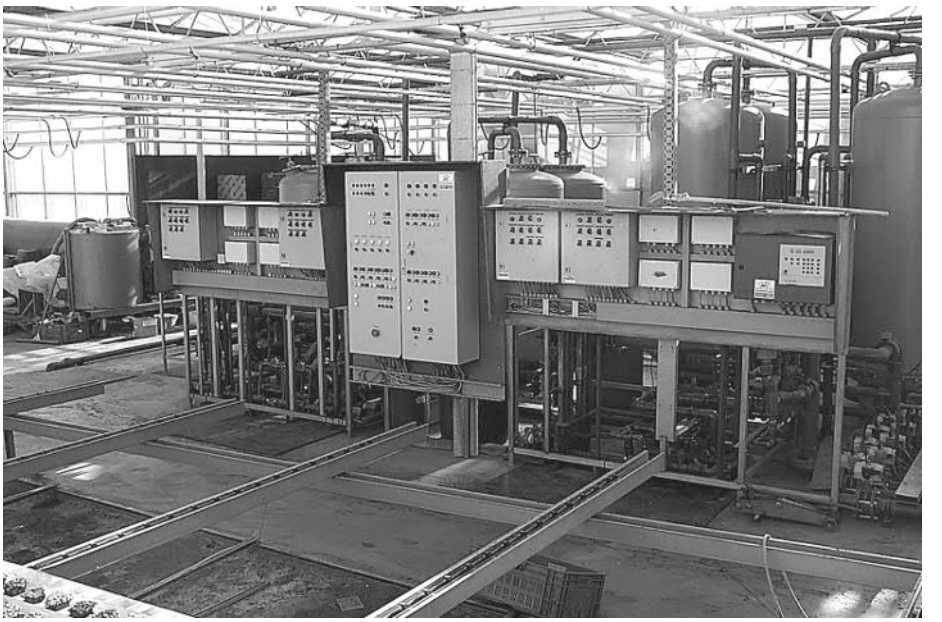

FIGURE 6.27 The central-computer-controlled solution treatment and injection systems with filters (tanks behind). (From Hortiplan, N.V., Belgium. With permission.)

going back to the plants (Figure 6.27). There are sand and charcoal filters in each system. There are two formulations, one for young plants, in trays and during the first 10 d in the gutters, and one for older plants, after the initial 10 d in the gutters until harvest. Five different irrigation zones exist on each growing field.

Overhead boom sprayers are located in each range of the greenhouse to apply pesticides when necessary (Figure 6.28). The greenhouse environment is enriched with carbon dioxide by use of burners located overhead. Supplementary high-intensity discharge (HID) lighting is also installed to improve light during the fall and winter months (Figure 6.29).

During harvesting, the automated system moves the gullies from the growing field to a belt that carries each tray to the packing area where workers remove and package the lettuce. After the lettuce is packed, the plastic bins with the lettuce pass through a misting system to moisten them before going into the refrigerator (Figures 6.30 and 6.31).

The lettuce varieties grown include Boston/Bibb, green and red oakleaf, Lollo Rossa, and trios (three plants per block: red oakleaf + Lollo Rossa + Lollo Bionda). These combinations give diversified products that are in high demand in the market (Figure 6.32). The products are sold with roots on to keep freshness. All products are sold through a Dutch auction system, much of it through electronic bidding online. For this reason, all growers must produce the same consistent quality of product, as purchasers expect the same quality regardless of the grower. The Belgian market demands large heads, of at least 400 g (a minimum of 1 lb) (Figures 6.33 through 6.35).

6.8 GREEN AUTOMATION LETTUCE SYSTEM

Green Automation Group Oy with headquarters in Helsinki, Finland and Green Automation Americas (www.greenautomation.com) in Wellington, Florida, have highly automated NFT systems of growing full-size lettuce such as Bibb and other leaf lettuce, and a system to grow baby leafy greens. Various levels of automation are available depending on the needs of the greenhouse operation and capital budget.

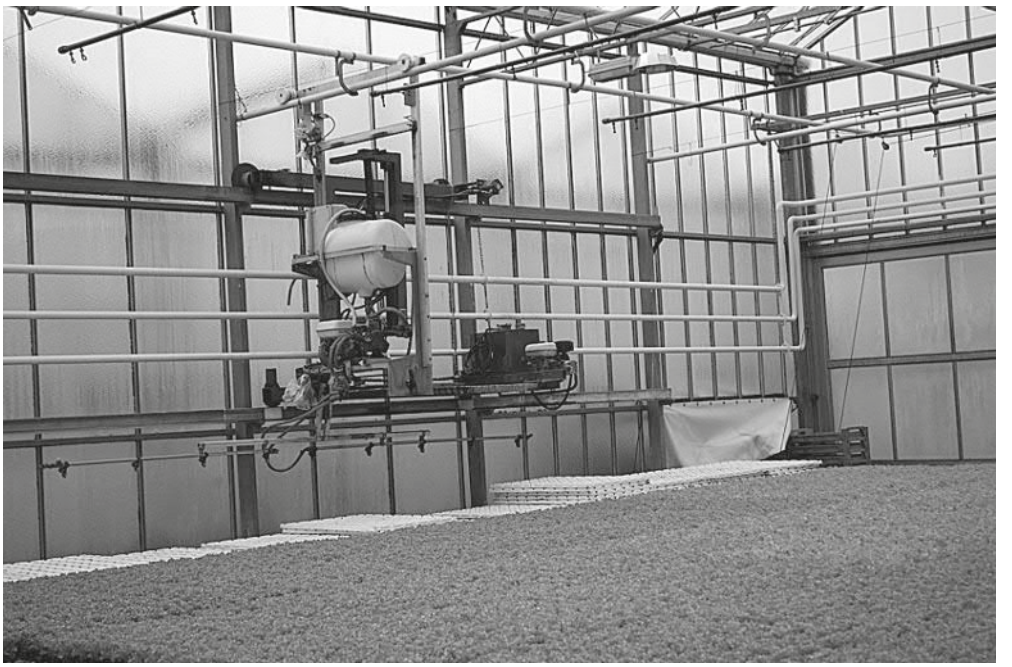

FIGURE 6.28 Overhead boom sprayer. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.29 HID lighting over a crop of green oakleaf lettuce. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.30 Harvesting lettuce from the NFT gutters as they move along on a conveyor belt. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.31 Packaged lettuce in tote bins moving under a misting system. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.32 Trio combination of leafy lettuces. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.33 Bibb lettuce head ready to harvest. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.34 Crop of Lollo Rossa lettuce ready to harvest. Note: The staggered spacing of the lettuce within the gutters. (From Hortiplan, N.V., Belgium. With permission.)

FIGURE 6.35 Finished product sleeved and packed in plastic tote bins. (From Hortiplan, N.V., Belgium. With permission.)

6.8.1 Living Lettuce System

This system for growing lettuce heads, living lettuce, and larger herbs is not as fully automated as the baby leaf lettuce system. In the living lettuce system small pots in trays are filled with a soilless peatlite substrate by an automatic pot filling machine (Figure 6.36). From there the pots in trays (54 pots per tray for 60 mm pots) pass through an automatic seeder followed by watering (Figure 6.37). Then they are manually transported up to 120 trays per pallet, to a climate-controlled germination chamber where precise temperatures and moisturizing are maintained. The trays remain stacked on the pallets for 2–3 d during germination (Figure 6.38).

After germination the pallets with stacked trays are transported to the nursery area of the greenhouse and manually placed on the nursery table where they are irrigated with an overhead boom irrigator (Figures 6.39 and 6.40). The seedlings remain in the nursery area for about 2–3 wk before transplanting to the NFT gutters (Figure 6.41).

Transplanting may be fully automated or done manually with a special planting fork that grasps six pots. The use of a fully automated transplanting system depends on the return on investment resulting from labor savings. For large greenhouse operations of 5–10 ha such automation could be justified. After transplanting the empty trays are returned to the processing area for washing and sterilization by a special washing machine.

The growing system moves the gutters automatically from the transplanting end to the harvest end on the table (line). During the growing process the distance between the gutters increases according to the spacing needs of the plants as they grow (Figures 6.42 through 6.45). Usually there are 5–6 spacing intervals.

During the growing process the plants in their gutters have moved to the harvest end of the growing line. There they are cut or picked manually, placed on a conveyor belt that takes them to

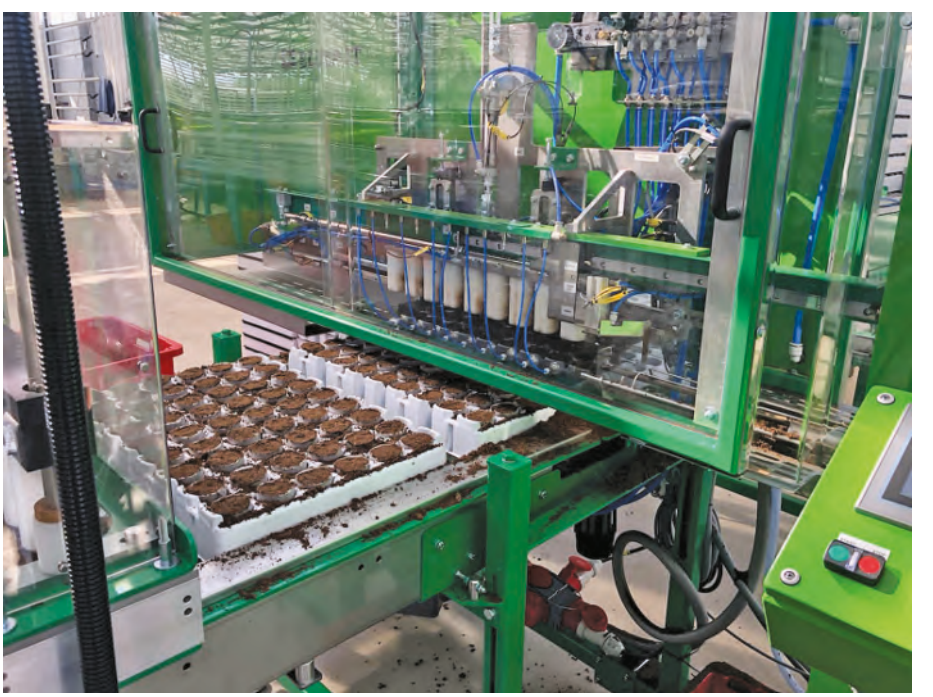

FIGURE 6.36 Pot filling machine. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.37 Automatic sowing line, includes pot filler, dibbler, and seeder (back to front). (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.38 Seeded trays of pots pass on conveyor belt to be stacked and enter germination chamber (in background). (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.39 Germinated seeds move to nursery table with overhead boom irrigator (upper left). (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.40 Seedlings grow on nursery tables having rollers so the trays may be moved toward the transplanting stage in the NFT gutters. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.41 Seedlings in trays on the nursery table ready to be transplanted. (From Green Automation Americas LLC, Wellington, FL. With permission.)

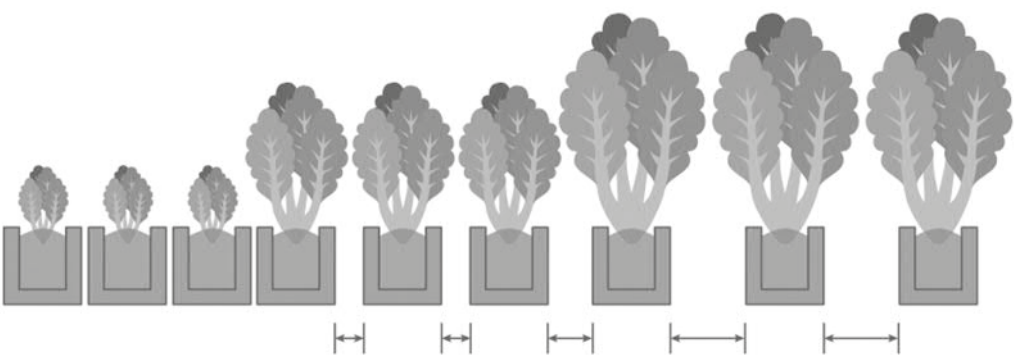

FIGURE 6.42 Automated gutter spacing as plants grow. (From Green Automation Americas LLC, Wellington, FL. With permission.)

the packing area (Figure 6.46) to be packed in plastic bags or sleeves (Figures 6.47 and 6.48). Cut leaves and waste parts as roots are transported by a belt to a waste bin. The gutters are placed to the automatic gutter washer located under the harvesting station. After the gutters are washed workers place them above on a gutter return wagon (Figure 6.46) for transport back to the transplanting area where the growing cycle is repeated.

It is possible to have different specific lines in the same greenhouse to grow different crops, like lettuce, basil, or arugula. With herbs, larger pots than that of the lettuce system can be used. The process is very similar to that of the lettuce. The pots in trays are filled by a machine, and then 15–20 seeds are sown per pot with an automated seeder. From there they are placed in the germination chamber for a few days where germination takes place. They are then transplanted to the nursery NFT system (Figure 6.49). Gutters for herbs may have larger diameter holes to fit the larger pots to

FIGURE 6.43 Gutters are automatically spaced as the lettuce plants grow in size. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.44 Bibb lettuce spaced nearing harvest stage. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.45 Mature Bibb and leaf lettuce ready to harvest. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.46 Harvesting lettuce, which is placed on belt to packing facility. Note: The gutters stacked above on the gutter return wagon after washing for reuse. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.47 Harvesting and sleeving in boxes that travel on belt to packing area. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.48 Lettuce entering bagging machine followed by packing into boxes. (From Green Automation Americas LLC, Wellington, FL. With permission.)

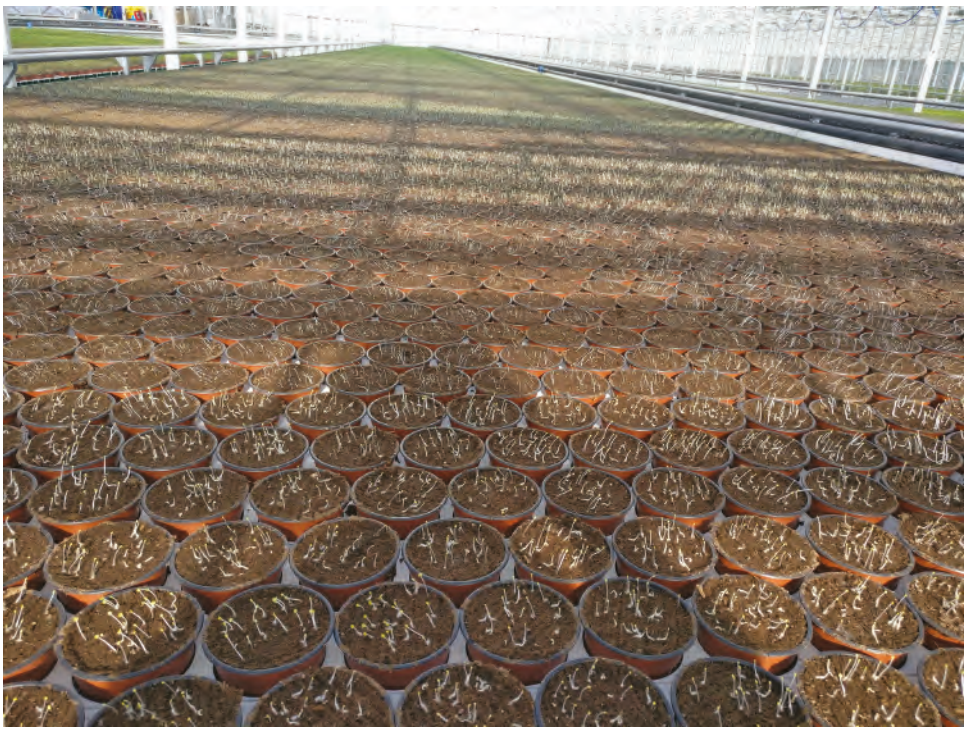

FIGURE 6.49 Basil in pots placed in NFT system. Note: In the foreground seedlings just moved from the germination chamber to this nursery section. (From Green Automation Americas LLC, Wellington, FL. With permission.)

have more space for seeds (Figure 6.50). The growing process continues with automated spacing as the plants grow and the gutters move from the transplanting to the harvesting end of the system (Figures 6.51 and 6.52).

The potted basil or other potted herbs are placed in sleeves manually on the harvest station at the harvest end of the NFT gutter system. The sleeved pots are placed on a belt that takes them to the packaging facility (Figures 6.53 and 6.54).

6.8.2 Green Automation Baby Leaf Greens System

Green Automation specializes in automated systems for leafy greens. In 2020 Green Automation Americas had installed their systems in nine locations in the United States. The baby leaf greens system is for growing baby leaf plants such as leaf lettuce, pac choi, mustard greens, red and green kale, and arugula. These are packaged as salad mixes.

Seeding is done directly into small gutters to avoid the need of transplanting. The narrow gutters may be filled with a soilless peatlite medium or a narrow strip of rockwool may be placed in the gutters (Figures 6.55 and 6.56). Seeds are sown with an automatic sowing machine (Figure 6.57).

From the seeding area the gutters are automatically transported by conveyor belts and a rotating turn table to the growing system (Figure 6.58). In the majority of the operations the germination takes place at the beginning of the growing inside an enclosed area ("Germination Box"). By having individual germination boxes for each growing line, the exact length of such a box can be tailored to the germination needs of the specific variety grown on that line. The length of the germination box is related to the time the seeds stay inside the germination box. As an option the system can be delivered

FIGURE 6.50 Basil about 1 wk old in pots placed in special NFT gutters. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.51 Basil ready to harvest. Note: Spacing between gutters. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.52 Basil in pots in NFT gutters. Note: The nutrient inlet lines to the gutters below. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.53 The sleeved herbs are transported on a belt to the packaging facility. Note: The lettuce traveling on the lower belt to the packing area. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.54 Sleeved pots of live basil placed in boxes for shipping. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.55 Gutters for baby leafy greens filled with peatlite medium by machine. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.56 Gutters for baby leaf greens filled with narrow strip of rockwool. (From Green Automation Americas LLC, Wellington, FL. With permission.)

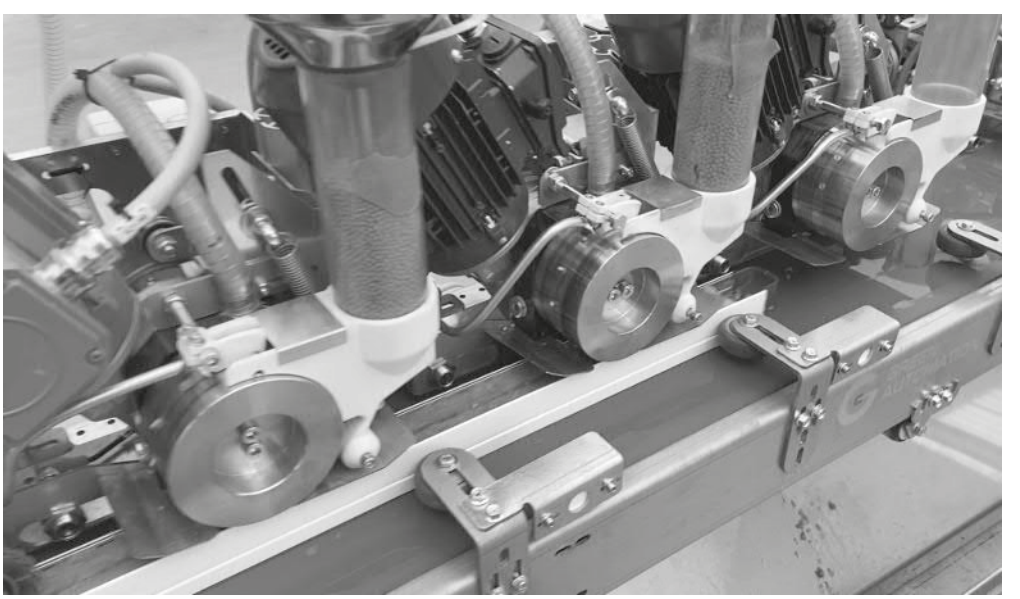

FIGURE 6.57 Sowing prilled (coated) seeds into rockwool of gutter. (From Green Automation Americas LLC, Wellington, FL. With permission.)

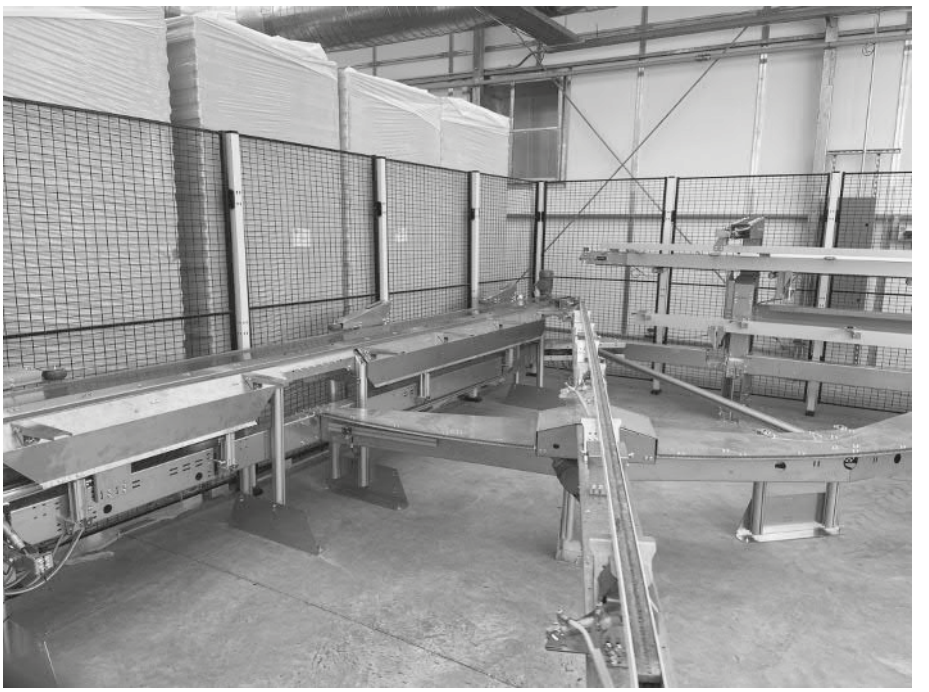

FIGURE 6.58 Seeded gutter travels to growing area by belts and turn table. (From Green Automation Americas LLC, Wellington, FL. With permission.)

with a lower level for the germination and early seedling growing phase. In this case, seeded gutters enter the germination area located under the main growing line (Figure 6.59). Irrespective of where the germination area is located, it is typically equipped with a fogging system to control humidity and temperature to promote germination over a 1–3 d period. In some cases mechanical chilling can be added. On systems with a lower level the gutters typically remain on the lower level for an additional 2–5 d after germination, starting the early growing phase there before they are lifted to the above main growing area by an electric elevator (Figure 6.60). Depending on how many days the plants are on the lower level, it can be equipped with NFT irrigation drippers as well as growing lights. On the main growing line, as with the living lettuce system, the gutters are spaced as the plants grow in size and move toward the harvest end of the growing line (Figures 6.61 through 6.65). It takes about 25 d from seeding to harvest.

As the crop reaches the harvest end, they are moved automatically by a conveyor belt system to the processing area where they are cut and mixed using conveyor belts before packaging (Figures 6.66 through 6.68).

The roots, waste leaves, and substrate move on a conveyor to a waste bin and the trays continue on to a washing machine (Figure 6.69) followed by steam sterilization before returning automatically on belts to the seeding area to repeat the cycle.

This growing system is "Hands Free" in that no human handling of the product occurs from sowing of seeds through bagging.

Green Automation claims their "Baby Leaf Greens" system in greenhouses will produce about 25 times that of field growing and use 90% less water than field-grown leafy greens. Their growing system is designed for commercial greenhouse operations of 1 acre (0.4 ha) and greater. Expected annual yields are 15 lb/ft^2 (75 kg/m^2) and more. From their experience in Finland, where the systems were developed, they use supplementary lighting to enable the high plant density and year-round

FIGURE 6.59 Lower level where seeds germinate in gutters, and upper level for post germination growing . (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.60 Handling elevator lifts germinated gutters to upper growing level. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.61 Baby lettuce in gutters of rockwool beginning to space. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.62 Baby leaf lettuce in rockwool substrate at full spacing ready to harvest. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.63 Gutter system using peatlite substrate growing arugula. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.64 Gutter system with peatlite substrate growing baby red leaf lettuce. Note: The spacing between the gutters as the plants mature. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.65 Gutter system with peatlite substrate growing arugula (foreground) and baby red leaf lettuce (background). (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.66 At the harvest end of the growing system the gutters are pushed mechanically onto the conveyor belt taking them to the processing area. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.67 The lettuce enter the cutting machine. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.68 Various lettuces are brought onto separate belts where they are mixed by entering the belt perpendicular to them. This front belt takes them to the packaging machine. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.69 Washing machine removes substrate and remaining plant materials before cleaning the gutter. (From Green Automation Americas LLC, Wellington, FL. With permission.)

growing within the greenhouse. To take advantage of economies of scale to maximize production efficiencies in order to achieve a competitive cost level compared to field growing, large scale operations of 15 acres (6 ha) should be the objective. Such large-scale operations operate in Finland and Estonia within 200–300 km of major population centers.

A typical layout of growing lines for a 1 ha (2.5 a) greenhouse with 7 ranges of 42 ft (12.8 m) wide are as follows. Six ranges (bays) would be for growing (0.9 ha or 2.22 a) and one bay for the processing tasks such as offices, cooler, storage, sowing, washing, and packing. Six lines each of 40 ft (12 m) in width or 12 lines each of 20 ft (6 m) in width. Assuming a targeted end weight of 8 oz (226 g), such configuration could yield about 4.65 million plants annually. This would be 17 crops yearly of about 270,000 plants per crop. Such production is equivalent to an annual yield of over 20 lb/ft^2 (100 kg/m^2) of the greenhouse growing area. Similar numbers can be achieved for Teen leaf and typical numbers for Baby leaf being slightly lower at about 15 lb/ft^2 (75 kg/m^2). Teen leaf is baby leaf that is grown larger (longer). Teen leaf plants each weigh from 30–80 g, whereas, baby leaf plants weigh less than 30 g. Of course, climatic factors of light and greenhouse growing conditions would impact the rotations and final size/weight of the heads. The addition of supplementary LED lighting in the greenhouse would be beneficial in increasing the number of annual cropping cycles and plant weight.

A fully automated irrigation/fertigation system includes water storage and filtration with fertilizer injectors (Figure 6.70). The fertigation process is monitored and operated by a touch screen pc control system (Figure 6.71). Electrical conductivity (EC) and *p*H sensors monitor and ensure that irrigation water remains in preset values. Automatic safety procedures interrupt the system should values reach hazardous/non-optimal levels.

All operations of the growing and processing systems are monitored and controlled by central computers having touch screens. The processes from seeding, transporting, boom irrigation, fertigation, and automated growing lines are monitored with software picture control systems using industrial touch screen computers (Figure 6.71). The control system software license includes customization of the software according to the customer's needs. This control system can be expanded to include all of the climate control systems for the greenhouse.

FIGURE 6.70 Fertigation system with water storage tank, filters, and computer controllers. (From Green Automation Americas LLC, Wellington, FL. With permission.)

FIGURE 6.71 Central touch screen computer system showing picture of the operation selected. Note: The right angle at the lower right is the turn table conveyor moving sown gutters to the growing lines. (From Green Automation Americas LLC, Wellington, FL. With permission.)

The overall capital cost for a fully automated growing system installed in a one-hectare (2.5-acre) greenhouse as described is between 2.4 and 3 million dollars. Due to the relatively high cost, the greenhouse operation must be located in the vicinity of a high population area so that rapid future expansions are possible with increasing market demand for the product. The most cost-effective size for this type of automated lettuce/leafy greens project is about 15 acres (6 ha) at which economies of scale are most beneficial.

6.9 EBB-AND-FLOW (FLOOD) SYSTEMS

The E&F technique is basically a subirrigation method. Nutrient solution is pumped into a shallow bed to a depth of about 1 in. (2–3 cm) for about 20 min and then allowed to drain back to the nutrient tank once the pumps are shot off. E&F benching or flood benching systems are available from commercial manufacturers such as Zwart Systems (Appendix 2). These bench systems are particularly suited for the growing of seedling transplants and ornamental potted plants (Figure 6.72). The bottom of the flood bench has small cross channels perpendicular to deeper channels (Figure 6.73). This allows uniform filling and complete drainage during the irrigation cycles. The deeper channels lead to the inlet-outlet pipes. Tables are irrigated from both ends. The tables are 50 ft (15 m) in length, supported by metal framing with concrete footings to maintain them perfectly level.

Another type of E&F system is the flood floors, as used by Bevo Agro Inc., in Langley, British Columbia, to propagate transplants for commercial greenhouse and field growers. They market to Canada, the United States, and Mexico. Since their incorporation in 1989, by 2018 they had expanded to a 53-acre (21.5-ha) facility. They specialize in tomatoes, cucumbers, and peppers for the greenhouse industry. However, they also grow many vegetable seedlings for field production and flowers for greenhouse production.

Seeds are sown using automated seeding machines into rockwool substrate in special Styrofoam trays. After the seedlings reach several-true-leaves stage, they are transplanted to rockwool or "Jiffy"

FIGURE 6.72 Ebb-and-flow benches. (From Zwart Systems, Beamsville, Ontario, Canada. With permission.)

FIGURE 6.73 Fill-drain channels of ebb-and-flow bed. (From Zwart Systems, Beamsville, Ontario, Canada. With permission.)

coco coir blocks (cucumbers: 4–5 d; tomatoes: 10–12 d; peppers: 12–14 d) and spaced 8 in. x 8 in. (20 cm x 20 cm). Tomatoes are also grafted for many clients. Grafting is done in a special grafting room. After grafting, the plants are held in the Styrofoam trays for an additional week or so until the graft union heals before transplanting them to the blocks and placing them in the ebb-and-flood system. Bevo Agro uses a special machine that carries the rockwool blocks to the flood system and spreads them apart as they come off the transport machine onto the concrete floor.

In this type of propagation, the entire floor of the greenhouse is concrete, which forms the basis of the ebb-and-flood recirculation system. The sides of each bed approximately 20 ft x 100 ft (6 m x 30.5 m) can be constructed of one layer of concrete bricks cemented together on edge. A slight slope from the edge to the center enables flooding and draining to occur from the middle of each bed by way of a sunken drain line (Figures 6.74 through 6.77). The center of the "V" is usually 1–1.5 in. lower than the edges. Water is pumped up a buried supply line until the depth at the top of the "V" has been achieved. Drainage is through the same supply pipe back to a cistern. The system requires about 5 min to fill and 7 min to drain. Solenoid valves on the main PVC headers control the irrigation cycles. The nutrient system is fully automated with a computerized controller. The greenhouse is heated with a natural-gas-fired boiler hot-water system with heating pipes buried in the concrete floor. By achieving optimum temperatures for the various crops, through combined bottom heating and overhead heating systems, healthy, vigorous tomato, cucumber, and pepper transplants are produced (Figures 6.74 through 6.78).

6.10 A-FRAME NFT SYSTEM

The arrangement of NFT gutters on an A-frame structure to increase the production of low-profile plants such as lettuce, arugula, and herbs has been tested on many occasions on a small scale. Such a system was originally designed for testing these crops in Taiwan in the late 1980s, and the system was shown in one of the previous editions of *Hydroponic Food Production.* However, such systems worked fine on a small scale but were never designed for larger production. In a conference in Costa

FIGURE 6.74 Tomatoes in rockwool blocks on concrete flood floor. Note: The plant support stakes in the blocks. (From Zwart Systems, Beamsville, Ontario, Canada. With permission.)

FIGURE 6.75 Peppers in rockwool blocks on concrete flood floor. Note: The floor is draining. (From Zwart Systems, Beamsville, Ontario, Canada. With permission.)

FIGURE 6.76 Peppers in rockwool blocks on flood floor. (From Zwart Systems, Beamsville, Ontario, Canada. With permission.)

FIGURE 6.77 Tomatoes growing in an ebb-and-flood system using coco coir blocks. These are Jiffy blocks, and each has two plants. (From Jiffy Products. With permission.)

FIGURE 6.78 Tomatoes in Jiffy coco coir blocks in an ebb-and-flood system. (From Jiffy Products. With permission.)

Rica in April 2011, a company from Colombia, Grupo Tecnico Aponte, presented their A-frame project near Bogota, Colombia (Aponte, 2011).

Bogota, Colombia, at an altitude of 2,600 m (8,530 ft), has a mild climate with night temperatures of about 6°C (43°F) and day temperatures about 18°C (65°F), with maximum and minimum extremes of 24°C and -5°C (75°F and 23°F). These conditions are quite favorable to the growing of cool-season crops like lettuce. In a greenhouse, the company constructed A-frames of light-weight metal tubing 2.1 m (6.9 ft) tall, 2 m (6.5 ft) wide at the base, and 20 cm (8 in.) wide at the top. The structures were 6 m (20 ft) long. Each frame supports sixteen 2-in.-diameter PVC pipes (Figure 6.79). Plant holes of 5 cm (2 in.) diameter were cut in the pipes at 15-cm (6-in.) centers for the plant sites. There are 40 holes per pipe, giving a total of 640 per A-frame (16 pipes with 40 holes). A 500 m^2 (5,380 ft^2) greenhouse would contain 30 of these A-frames. Irrigation to the pipes is by a drip tube to each pipe. The pipe ends have a cap, and nutrient solution is not re-circulated. The solution is pumped from a cistern.

Plants are started in plastic containers of a coco coir and rice hull mixture (Figure 6.80). They are grown in a nursery area of closely spaced pipes with NFT (Figure 6.81) before being transplanted to the A-frames (Figures 6.82 and 6.83). Lettuce is ready to harvest in 7 wk (Figure 6.84). The individual plants are sold as sleeved and retained with their roots in the growing pots.

Ricardoes Tomatoes & Strawberries is located near Port Macquarie, NSW, Australia. They have 3 acres (1.2 ha) of greenhouses growing tomatoes and strawberries. Their strawberry facility grows two varieties of strawberries, with over 140,000 plants growing in an A-frame NFT system (Figures 6.85 through 6.89). They designed the system using PVC pipes.

Strawberry plants are propagated from runners. The runners are placed in plastic cups with two pieces of rockwool supporting them (Figure 6.85). The cup with its plant is placed in the PVC A-frame system. They are irrigated by a drip line at the top of each pipe in the A-frame (Figure 6.86). The spaghetti lines coming from a black poly hose along the top of the A-frame have no emitters so that flow is full, not a drip. One trickle line is connected to each pipe. Irrigation cycles are 15 min on followed by 15 min off during the summer and less frequent in the winter. The water flows down

FIGURE 6.79 A-frames with 16 NFT pipes each. (From Grupo Tecnico Aponte, Bogota, Colombia. With permission.)

FIGURE 6.80 Starting lettuce seedlings in plastic pots with coco coir-rice hulls substrate. (From Grupo Tecnico Aponte, Bogota, Colombia. With permission.)

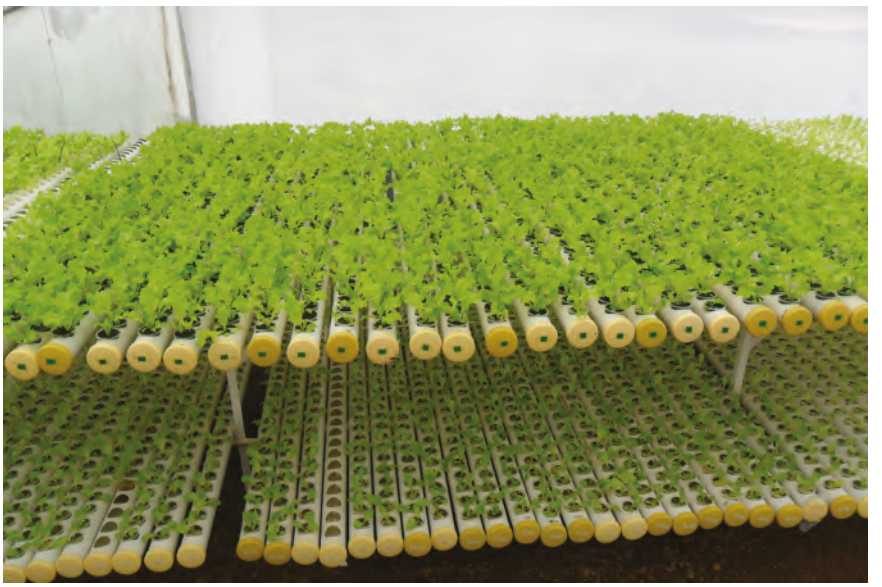

FIGURE 6.81 Nursery area of NFT pipes on two-level bench system. (From Grupo Tecnico Aponte, Bogota, Colombia. With permission.)

FIGURE 6.82 Lettuce seedlings transplanted to NFT pipes of A-frame. (From Grupo Tecnico Aponte, Bogota, Colombia. With permission.)

FIGURE 6.83 Lettuce in pots of coco coir-rice hull substrate in NFT pipes. View is from underneath A-frame. (From Grupo Tecnico Aponte, Bogota, Colombia. With permission.)

FIGURE 6.84 Lettuce at 7 wk ready to harvest. (From Grupo Tecnico Aponte, Bogota, Colombia. With permission.)

FIGURE 6.85 Strawberry plant propagated from runner placed between pieces of rockwool in a plastic cup. (From Ricardoes Tomatoes & Strawberries, Port Macquarie, NSW, Australia. With permission.)

FIGURE 6.86 Strawberries in PVC pipe A-frame. Note: Spaghetti tube irrigation at top of each pipe holding the plants. No emitters on irrigation tubes. (From Ricardoes Tomatoes & Strawberries, Port Macquarie, NSW, Australia. With permission.)

FIGURE 6.87 A black poly irrigation line attached to an underground main is located at the upper part of the A-frame. Collection pipes at the bottom of the growing pipes return the solution to a cistern by an underground main collection pipe. (From Ricardoes Tomatoes & Strawberries, Port Macquarie, NSW, Australia. With permission.)

the PVC pipe and is collected at the bottom by a catchment pipe (Figure 6.87) that flows into an underground main return to the cistern. The black poly lateral irrigation lines to each A-frame are connected to an underground main supply line from the nutrient solution tank.

There are over 4,000 m^2 (1 acre) of greenhouses growing strawberries. These are saw-toothed structures with roll-up poly sidewalls (Figure 6.90). The top and side vents serve for natural ventilation and cooling. No heating system is incorporated into the structures as the climate in the region is favorable to year-round growing of strawberries. There is a cooling system for each house for summer use.

They also grow tomatoes in a climate-controlled greenhouse of 8,000 m^2 (2 acres), which has hot water heating by use of a boiler that burns nut shells as the source of heat (Figure 6.91). The greenhouse is attached to a café/store at one end with a view to the public from the restaurant (Figures 6.92 and 6.93).

This is a very unique operation that attracts both local and international tourists. It is very family friendly and permits both parents and children to experience the growing of the strawberries in the

FIGURE 6.88 View of A-frames with strawberry plants. (From Ricardoes Tomatoes & Strawberries, Port Macquarie, NSW, Australia. With permission.)

FIGURE 6.89 Central passageway with A-frame section on left connected to main return. A-frames in the section on the right flow to the far right end where the collection main is located. (From Ricardoes Tomatoes & Strawberries, Port Macquarie, NSW, Australia. With permission.)

FIGURE 6.90 Saw-tooth greenhouses with roll-up sidewalls and roof ventilation for cooling. (From Ricardoes Tomatoes & Strawberries, Port Macquarie, NSW, Australia. With permission.)

FIGURE 6.91 Tomato poly greenhouse with double roof vents and boiler that uses nut shells for fuel. Note: Boiler in shed and pile of nut shells at side. (From Ricardoes Tomatoes & Strawberries, Port Macquarie, NSW, Australia. With permission.)

FIGURE 6.92 Tomato greenhouses attached to Café Red restaurant and store. (From Ricardoes Tomatoes & Strawberries, Port Macquarie, NSW, Australia. With permission.)

FIGURE 6.93 Restaurant with view to tomatoes growing in the attached greenhouse on right. (From Ricardoes Tomatoes & Strawberries, Port Macquarie, NSW, Australia. With permission.)

FIGURE 6.94 Pasta sauces and jams sold at Ricardoes Tomatoes café store. (From Ricardoes Tomatoes & Strawberries, Port Macquarie, NSW, Australia. With permission.)

A-frame hydroponic system. They are allowed to pick their own strawberries so it is a type of U-pick attraction. The visitors take picked fruit to the store to be bagged and weighed for take away. This is an agro-tourist operation that teaches visitors about the growing of strawberries and tomatoes hydroponically. The comment from visitors is that Ricardoes is an educational, enjoyable family outing. At the same time they may stay for lunch and shop for pasta sauce, jams, and other gifts (Figure 6.94).

Nothing goes to waste as second-grade fruit is diverted to jams, relishes, sauces, and so on. They even recycle the spent coco coir used to grow the tomatoes by selling it to home gardeners.

6.11 SUMMARY

The future of successful hydroponic crop production lies in a universal cropping system in which water and fertilizers can be used efficiently. This is particularly true in arid regions of the world, such as the Middle East, where land is nonarable and water is scarce. In such areas, desalinated sea water can be used, but is very costly. In the past, sand culture was used in many of these areas, but often it was of calcareous nature, which caused rapid changes in *p*H and tying-up of essential elements such as iron and phosphorus. In these areas of high solar energy, efficient use of costly desalinated water is essential.

The NFT is one such hydroponic systems that makes efficient use of water and fertilizers and at the same time does not rely on a locally suitable medium such as noncalcareous sand or gravel.

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7 Gravel Culture

7.1 INTRODUCTION

Gravel culture was the most widely used hydroponic technique from the 1940s through the 1960s. During the late 1960s and early 1970s one commercial operation, Hydroculture, near Phoenix, Arizona, had almost 20 acres (8 ha) of greenhouses in gravel culture. Many smaller commercial greenhouses throughout the United States used gravel culture as it was well documented and several companies such as Hydroculture were selling "mom and pop" packages to people interested in setting up their own hydroponic greenhouse.

W.F. Gericke introduced hydroponics commercially using gravel culture. It was used in most outdoor operations established during World War II on nonarable islands, as mentioned in Chapter 1. Gravel culture is still useful in areas having an abundance of volcanic rock, such as the Canary Islands and Hawaii. Today, nutrient film technique (NFT), rockwool, coco coir, and perlite cultures are more widely accepted as they have more consistent properties, are easier to sterilize between crops, and are less laborious to handle, maintain, and manage.

7.2 MEDIA CHARACTERISTICS

Some of the general characteristics media should possess have been discussed in Chapter 4. The best choice of gravel for a subirrigation system is crushed granite of irregular shape, free of fine particles less than 0.063 in. (1.6 mm) in diameter and coarse particles more than 0.75 in. (1.9 cm) in diameter. Over half of the total volume of particles should be about 0.5 in. (1.3 cm) in diameter. The particles must be hard enough not to break down, able to retain moisture in their void spaces, and drain well to allow root aeration.

The particles should not be of calcareous material – in order to avoid *p*H shifts. If only calcareous material is available, the amount of calcium and magnesium in the nutrient solution will have to be adjusted according to the levels of these elements released by the aggregate into the nutrient solution. The calcium carbonate in calcareous aggregates such as limestone and coral gravels reacts with the soluble phosphates of the nutrient solutions to produce the insoluble di- and tri-calcium phosphates. This process continues until the surfaces of the calcareous aggregate particles are coated with insoluble phosphates. After they are thoroughly coated, the reaction slows down to a point at which the rate of decrease of phosphates in the nutrient solutions is slow enough to maintain phosphate levels.

A new unused aggregate containing more than 10% of acid-soluble materials calculated as calcium carbonate should be pretreated with soluble phosphates to coat the particles with insoluble phosphates (Withrow and Withrow, 1948). The aggregate is treated with a solution containing from 500 to 5,000 g of treble superphosphate per 1,000 L or 5–50 lb per 1,000 gal. The new gravel should be soaked for several hours. The *p*H of the solution will rise as its phosphate content decreases. If the phosphate concentration drops below 300 ppm (100 ppm of P) after 1–2 h of soaking, the solution should be drained to the reservoir and a second phosphate addition made to the solution, which is repumped into the beds. This should be repeated until the phosphate level stays above 100 ppm (30 ppm of P) after several hours of exposure to the gravel. When this occurs, it indicates that all of the carbonate particles have been coated with phosphates. The *p*H of the solution will then remain about 6.8 or less. The phosphate solution then is drained from the reservoir, and the reservoir filled with fresh water. The beds are flushed with this fresh water several times, and once again the reservoir drained and refilled with fresh water. The beds may then be planted.

DOI: 10.1201/9781003133254-7

Over time the *p*H will begin to rise as the phosphates become depleted and free calcium carbonate is exposed on the surface of the aggregate. The process of phosphate treatment will then have to be repeated.

Schwarz and Vaadia (1969) have demonstrated that pretreated calcareous gravel or washed calcareous gravel could not prevent lime-induced chlorosis. The high *p*H of calcareous gravel also makes iron unavailable to plants. Victor (1973) found that daily addition of phosphorus and iron at the rate of 50 mL of phosphoric acid and 12 g of chelated iron (FeEDTA) per 1,000 gal (3,785 L) of nutrient solution prevented the occurrence of lime-induced chlorosis with tomato plants.

"Haydite" or "Herculite" fired shale, available in a variety of particle sizes, is often used by smaller backyard hydroponic units. It is porous and has given good results in many cases. However, after continued use, the adsorption of fertilizer salts on the surfaces of the particles may cause difficulty. The absorbed salts are not easily removed by washing. Plant roots become lodged in the small pores of the rock surface, making sterilization of the medium between crops difficult. Also, the material fractures and breaks up into small pieces, which eventually form a fine sand and silt that plugs feeder lines and pipes.

If a drip trickle feeding system is used rather than a subirrigation system, a smaller medium must be used. For such a system, "pea" gravel between 0.13 and 0.38 in. (3–10 mm) in diameter should be used. Over half of the total volume of gravel should have a particle size of 0.19–0.25 in. (5–6 mm) diameter. No silt or particles larger than 0.38 in. (10 mm) in diameter should be present. Haydite gravel is particularly suitable for a trickle feeding system because its capillary action moves the nutrient solution laterally around the plant root system. However, as plant roots grow laterally they also will intercept the water and cause it to flow laterally.

7.3 SUBIRRIGATION GRAVEL CULTURE

Almost all gravel culture uses a subirrigation system. That is, water is pumped into the beds, which floods them within several inches of the surface, then drains back to the nutrient reservoir. This is similar to the ebb-and-flood system discussed in Chapter 6. Such a system is termed *closed* or *recycled* since the same nutrient solution is used each pump cycle over a period of 2–6 wk. Then the solution is disposed of and a new solution made up.

The frequency and duration of irrigation cycles is important to the success of the system. Each irrigation cycle must provide adequate water, nutrients, and aeration to the plant roots.

7.3.1 Frequency of Irrigation

The minimum frequency of irrigation depends on the following factors:

1. The size of the aggregate particles
2. The surfaces of the aggregate particles
3. The nature of the crop
4. The size of the crop
5. Climatic factors
6. Time of day

Smooth, regularly shaped, coarse aggregates must be irrigated more frequently than porous, irregularly shaped, fine aggregates having large surface areas. Tall crops bearing fruit require more frequent irrigation than short-growing leafy crops such as lettuce, because of their greater surface area and therefore higher evapotranspirational losses. Hot, dry weather promotes rapid evaporation and makes more frequent irrigation necessary. During midday when light intensities and temperatures are highest, the period between irrigation cycles must be reduced.

For most crops, the aggregate must be irrigated at least three to four times per day during dull winter months, and in summer it is often necessary to irrigate at least every hour during the day. Pumping at night is not necessary. In temperate zones, during the summer, irrigation should be from 6:00 a.m. to 7:00 p.m., while during the winter it may be set up from 8:00 a.m. to 4:00 p.m.

Water is absorbed by the plant from the nutrient solution much more rapidly than the inorganic elements. As a result, the films of nutrient solution on the aggregate become concentrated with inorganic salts as absorption takes place. The concentration of the nutrient solution in the aggregate becomes greater as the rate of transpiration of the plants increases, and the rate of water absorption thus increases. By increasing the number of irrigation cycles, the high water demand of the plant is met and the water content within the void spaces of the gravel is maintained at a more optimal level. In this way, the nutrient solution does not become so concentrated between irrigation cycles. It is also necessary to irrigate frequently so that the films of nutrient solution over the aggregate particles in contact with the root tips are not depleted of any nutrient between irrigations.

Immediately following irrigation, the nutrient solution in the aggregate has nearly the same composition as the reservoir solution. As absorption proceeds, the composition of the nutrient solution in the bed continually changes, including the proportion of the various ions, the concentration of the solution, and the *p*H. If the frequency of irrigation is not sufficient, nutrient deficiencies may develop, even though adequate quantities of nutrient elements may be present in the reservoir solution. If the aggregate does not contain a large proportion of fine particles, it is unlikely that frequent irrigation will cause aeration problems so long as the beds are completely drained between irrigations and the irrigation period is not too long. The more often the beds are irrigated, the more nearly the composition of the aggregate solution approaches that of the reservoir solution.

7.3.2 Speed of Pumping and Drainage

The speed of pumping and draining of the nutrient solution from the gravel determines the aeration of the plant root system. Roots require oxygen to carry on respiration, which in turn provides the energy needed in the uptake of water and nutrient ions. Insufficient oxygen around the plant roots retards their growth or may cause death, which results in plant injury, reduced yields, and eventually plant death.

In a subirrigation system, as the nutrient solution fills the gravel voids from below, it pushes out air that has a relatively low content of oxygen and a high content of carbon dioxide. Then, as the nutrient solution flows from the gravel, it sucks air into the medium. This new supply of air has a relatively high content of oxygen and a low content of carbon dioxide. The greater the speed of solution movement in the gravel medium, the greater the speed of air displacement. Also, since the solubility of oxygen in water is low, the period of low oxygen supply while the free water is in the gravel is shortened if the speed of filling and draining is rapid.

A 10- to 15-min period for filling and draining, or a total time of 20–30 min, is generally acceptable. In the removal of the free solution from the bed, nothing less than complete drainage is recommended. Only a film of moisture on the gravel particles is desired. If puddles of solution remain in the bottom on the plant bed, poor plant growth results. This rapid filling and draining of the growing beds can be achieved by use of large pipes in the bottom of the beds. In summary, proper irrigation cycles should (1) fill the bed rapidly, (2) drain the bed rapidly, and (3) get all the solution out.

7.3.3 Effect of Irrigation Cycle on Plant Growth

By reducing the number of times of nutrient solution pumping, the moisture content in the gravel medium is lowered. This has a concentrating effect on the nutrient ions contained in the water film on the gravel particles. Whenever the osmotic concentration of the nutrient solution is increased, the

water-absorbing power of the plant is reduced, also reducing the nutrient ion uptake. Consequently, the rate of plant growth is retarded and a harder and firmer type of growth develops.

In the greenhouse during the dark, cloudy, short days of winter, reduction of the number of irrigation cycles per day will help keep the plants reasonably hard and sturdy.

7.3.4 Height of Irrigation

The nutrient solution level should rise to within about 1 in. of the surface of the aggregate. This practice keeps the aggregate surface dry, preventing the growth of algae, and reduces the loss of water and high humidity buildup at the base of the plants. It also prevents the growth of roots into the top inch of the aggregate surface, which, under conditions of high light intensities, may become too high in temperature for satisfactory root growth. The nutrient level in the beds can be regulated by installation of overflow pipes in the plenum. These construction details are discussed in Section 7.3.6.

7.3.5 Nutrient Solution Temperature

In greenhouse culture, the temperature of the nutrient solution should not fall below the night air temperature of the house. The temperature of the solution in the reservoir sump may be raised by use of an immersion heater or electric heating cable. Be careful not to use any heating elements having lead or zinc sheathing, as these can be toxic to the plants. Stainless steel or plastic-coated cables are best. Electric heating lamps have also been used successfully. In many locations, the temperature of the outside water used to fill the sump may be as low as 45–50°F (7–10°C). If a large reservoir needs to be filled, it should be done later in the day after the last irrigation cycle has been completed. Then there will be sufficient time before the next irrigation cycle the following morning for the heating unit to bring the solution temperature to a more optimal level.

In no case should heating cables be placed in the growing beds themselves. This causes localized high temperatures around the heating elements, which injure the plant roots.

7.3.6 Greenhouse Subirrigation System

7.3.6.1 Construction Materials

Since fertilizer salts used in making up the nutrient solution are corrosive, any metal parts, such as pumps, pipes, or valves, exposed to the nutrients will wear out in a very short time. Galvanized materials may release sufficient zinc to cause toxicity symptoms in the plants. Copper materials cause the same problem. Plastic pipes and fittings, pumps with plastic impellers, and plastic tanks are noncorrosive and should be utilized. Plant beds can be built of wood and lined with 20-mil vinyl.

During World War II, concrete was used in numerous commercial operations. It has the advantage of permanence and corrosion resistance, but its cost is the highest. Cedar or redwood is the most often used construction material, and direct lining of compacted normal ground substrate is the cheapest for bed construction.

7.3.6.2 Beds

The beds must be designed to provide rapid filling and draining – and complete drainage. The use of a 3-in. (7.6-cm)-diameter PVC pipe and a V-shaped bed configuration will fulfill these watering requirements (Figure 7.1). The beds should have a minimum width of 24 in. (61 cm), a depth of 12–14 in. (30.5–35.5 cm), and a maximum length of 120–130 ft (36.5–40 m). The beds should slope from 1 to 2 in. (2.5–5 cm) per 100 ft (30.5 m). Water enters into and drains from the beds through small 0.3- to 0.5-in. (0.64- to 1.27-cm)-diameter holes or 0.13-in. (0.32-cm)-thick saw cuts on the

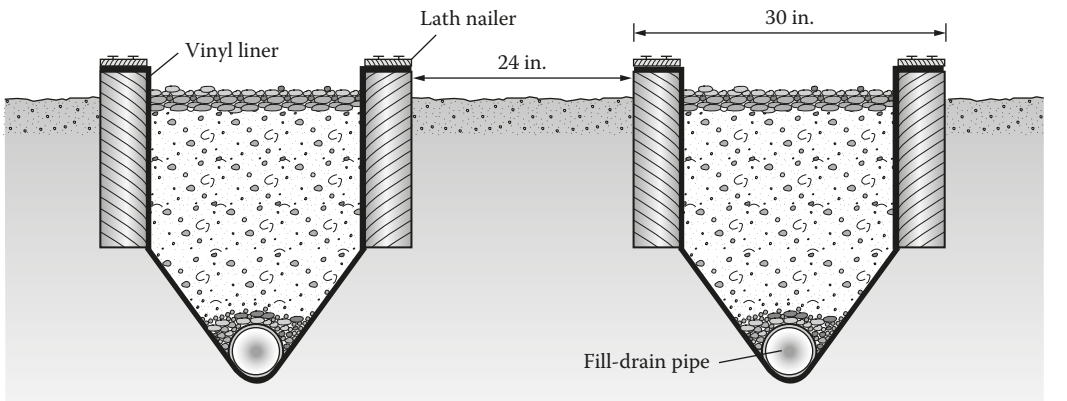

FIGURE 7.1 Cross section of subirrigation gravel bed. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

bottom one-third of the PVC pipe. These holes or saw cuts are made every 1–2 ft (30.5–61 cm) along the entire length of the pipe.

The inclination can be achieved by sloping the sideboards and staking them. In some cases, growers may pour concrete walkways between these beds. The beds should be constructed in compacted river sand. A jig containing the desired configuration can be used to dig out the bed (Figure 7.2). Once the proper configuration and slope have been compacted, the beds are lined with a vinyl liner of 20-mil thickness commonly used for swimming pools (Figure 7.3). The 3-in.-diameter PVC fill-drain pipe is then set in place with holes or cuts facing downward to prevent roots readily growing with the holes or cuts facing downward to prevent roots readily growing into the pipe. The vinyl is held on the sides of the beds by folding it over the rough 2-in.-thick cedar side planks and nailing with a wooden strip on top of its entire length.

The PVC pipe allows water to flow rapidly along the bottom of the beds, and fills and drains the beds equally and vertically along the entire length. With this rapid filling and draining, old air is pushed out of the aggregate and new air is sucked in as discussed earlier.

The beds should be filled with gravel to within 1 in. of the top at the end near the nutrient tank and within 2 in. at the far end. To prevent uneven near-surface moistening during the irrigation cycles, level the top surface of the gravel. Remember that the beds are not level, but water remains level; so, with the top surface of the gravel leveled, the water level in the flooded beds will be parallel to the gravel surface. If the gravel were placed to within 1 in. of the top of the bed along the entire length, it really would have a 1-in. slope and therefore if during the irrigation cycle the beds were filled to within 1 in. of the gravel surface at the reservoir end of the beds, it would be 2 in. from the top at the far end. This would cause uneven watering of the plant roots from one end to the other end of the beds. Recently transplanted seedlings might suffer a water stress at the far end due to insufficient height of water in the bed. If the water level were within 1 in. at the distant end, it would come to the surface at the reservoir end, creating problems of algae growth.

The 3-in. PVC pipe should have a 45° elbow, and project above the gravel surface with a cap at the far end from the tank to allow for cleaning of the pipe. Usually the pipes are cleaned of roots every year or so with a "snake" rooter machine. The end of the pipe at the reservoir drains into a plenum.

7.3.6.3 Plenum

Filling and draining times can be greatly decreased by the use of a plenum rather than solid plumbing from the pump(s). The plenum is simply a trough into which the water is pumped from the tank. The 3-in. PVC pipes running along the bottom of the beds open into this plenum (Figures 7.4 through

FIGURE 7.2 Digging bed configuration in compacted river-sand fill.

FIGURE 7.3 Vinyl liner placed into beds and PVC drain pipes location.

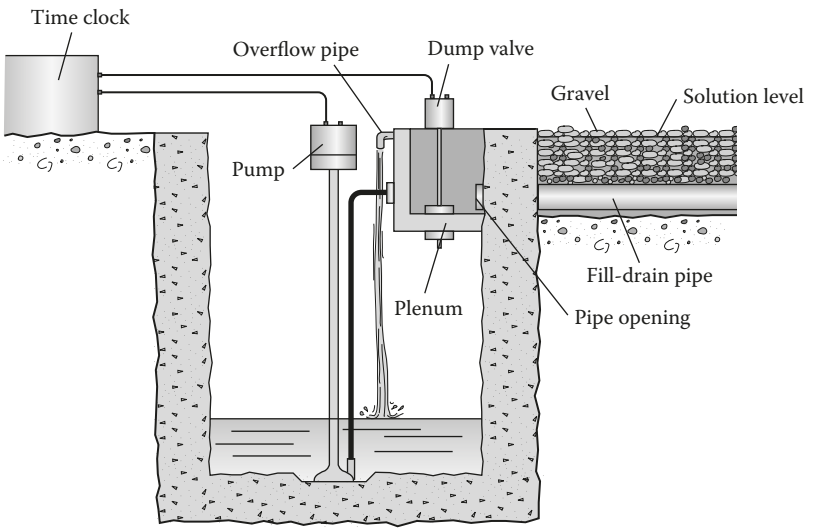

FIGURE 7.4 Cross section of plenum and nutrient tank. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

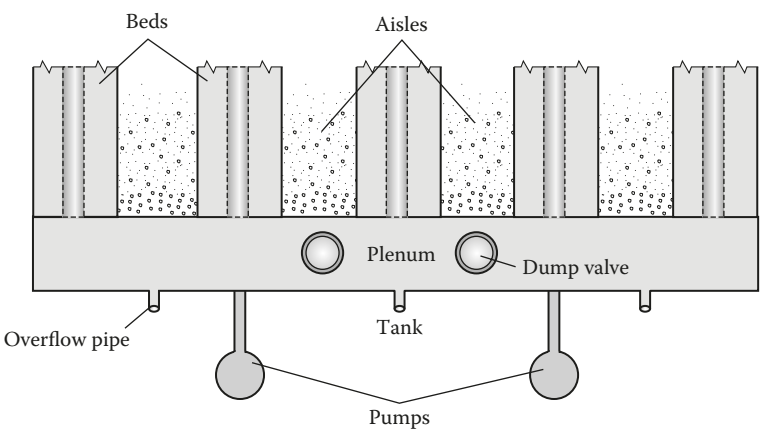

FIGURE 7.5 Plan view of plenum and nutrient tank. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

7.6). The bed pipes must be sealed into the plenum, or water will leak behind the tank, resulting in loss of nutrient solution and buildup of water under the greenhouse and tank.

Either a sump or submersible pumps may be used to pump the nutrient solution from the reservoir into the plenum. The pump is activated by either a time clock or a feedback mechanism attached to a moisture sensor in the beds. The water level in the beds is regulated by an overflow pipe in the plenum. The plenum and beds will fill to a level that corresponds to 1 in. below the gravel surface in the beds. A dump valve, activated by the same time clock or feedback mechanism as the pumps, closes the drain holes of the plenum while the pumps are operating (Figure 7.4).

The operation is as follows:

1. The moisture sensor in the bed signals the feedback mechanism to turn on the pumps (or the preset time clock strikes an irrigation cycle) and activates the plenum valves.

FIGURE 7.6 Bed fill-drain pipe entering plenum.

2. The pumps are activated; the dump valves of the plenum close.
3. The plenum and beds begin to fill.
4. They continue filling until excess solution spills back into the tank via the overflow pipes.
5. The preset irrigation period terminates; the beds are full of solution.
6. The pumps stop, the dump valves fall open, the nutrient solution drains from the beds back to the plenum, and finally falls into the tank, being well aerated.
7. The whole cycle of pumping and draining should be completed within 20 min.

7.3.6.4 Nutrient Tank

The nutrient tank must be constructed of a watertight material. Steel-reinforced concrete 4 in. (10 cm) thick, coated with a bituminous paint to make the concrete watertight, is the most long-lasting material. The plenum should be a part of the tank so that leakage cannot occur between them. The volume of the tank must be sufficient to completely fill the gravel beds, based on the amount of void space in the gravel. This can be determined by taking a sample of the rock (about a cubic foot) and filling it with water, then measuring the volume of water required to fill the void spaces. Then extrapolate to calculate the total void space in all the beds. The tank should hold a volume 30–40% greater than the total volume required to fill the beds. For example, a tank of about 2,000 Imp. gal (9,092 L) would be required to supply 5 beds 2 ft (61 cm) wide x 12 in. (30.5 cm) deep x 120 ft (36.5 m) long (Figure 7.7).

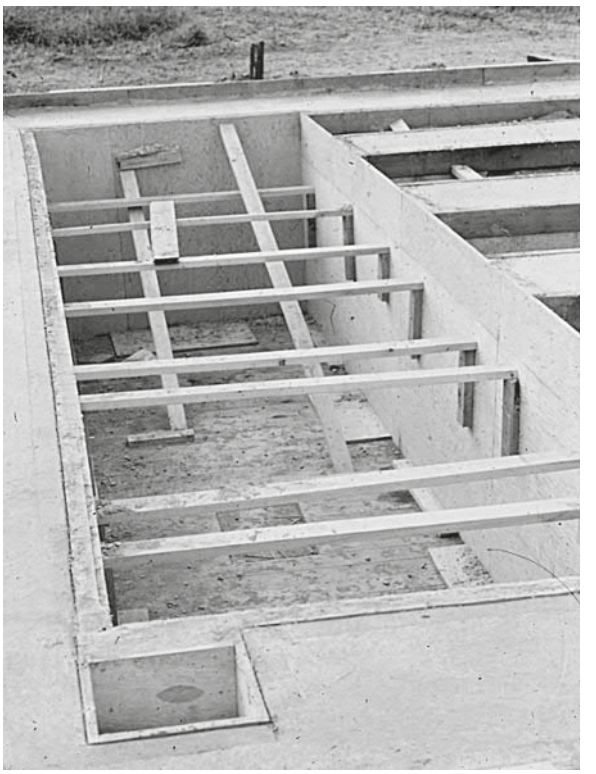

FIGURE 7.7 Nutrient tank construction.

An automatic float valve could be attached to a water refill line in order to maintain the water level in the tank. In this way, water lost during each irrigation cycle through evapotranspiration by the plants would immediately be replaced. The nutrient tank should have a small sump in which the pumps sit in order to facilitate complete drainage and cleaning of the tank during nutrient changes (Figure 7.4).

The tank-plenum could be changed somewhat in structure to reduce its size. This can be done (as shown in Figure 7.8) by dividing the plenum into two parts, each servicing three beds. A three-way automatic valve would discharge the nutrient solution alternately into one plenum on activation of the pumps and dump valve, filling three beds during each cycle (Figure 7.9). In this case, a time clock, rather than a moisture-sensor feedback system, must be used, with shorter intervals between irrigation cycles than those required for one larger plenum as described earlier.

The pump could also be piped into a discharge line, which could be connected to the outside drainage system. Gate valves would be used to control the direction of flow of the nutrient. When the nutrient solution is changed, the gate valve in the waste line is opened and the solution is pumped out to waste. Normally during regular feeding cycles, this waste valve is closed and the valve between the pump and the three-way valve is open. The three-way valve is available commercially.

By using such a split plenum, the tank capacity can be reduced to almost half the volume of one large enough to fill all six beds at once. Thus, a tank of 1,200 Imp. Gal. (5,455 L) should easily supply three gravel beds 24 in. (61 cm) wide x 12 in. (30.5 cm) deep x 120 ft (36.5 m) long.

An overall plan of a gravel culture system having six beds and the attached plenum and nutrient tank is illustrated in Figure 7.10. Successful crops of high productivity can be grown with a subirrigation gravel system, as illustrated in Figures 7.11 and 7.12.

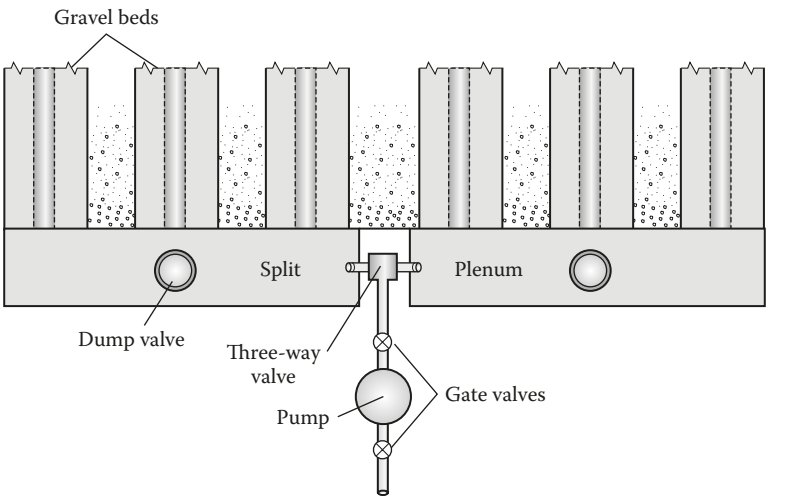

FIGURE 7.8 Plan view of nutrient tank with a split plenum. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

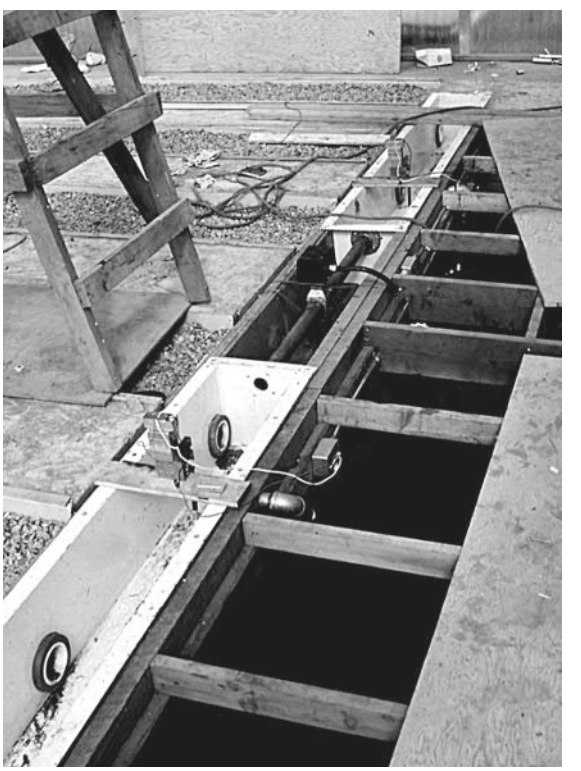

FIGURE 7.9 Three-way automatic valve used with a split-plenum design.

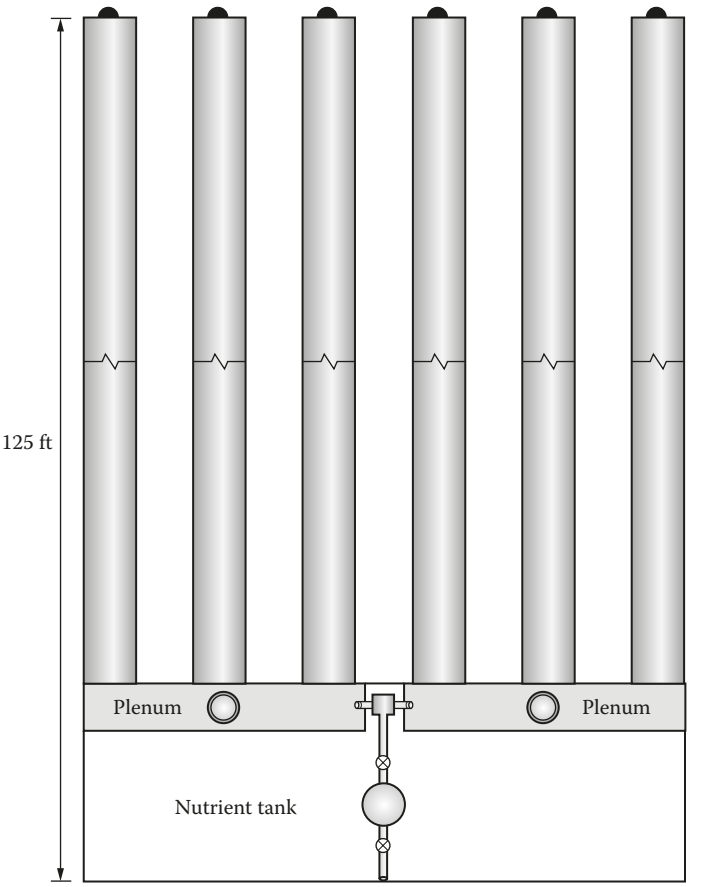

FIGURE 7.10 Plan of a greenhouse with six gravel beds and split-plenum nutrient tank.

(Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

7.4 TRICKLE-IRRIGATION DESIGN

The bed design and construction of trickle-irrigation systems are similar to that of subirrigation systems, but a smaller tank (cistern) is needed as the beds do not need to be filled with solution. This is a closed, recycling system similar to subirrigation gravel culture. The nutrient solution is applied to the base of every plant by a drip line or ooze-hose. The solution percolates through the gavel and plant roots and is returned to the cistern through a large drainage (3-in. PVC) pipe similar to subirrigation. The bed drain pipes connect to a main return line that conducts the solution back to the nutrient tank. The nutrient tank should therefore be placed at a lower end of the greenhouse so that all drain pipes can slope to that point. The use of smaller gravel (0.13–0.25 in. in diameter) with the trickle system is essential to facilitate lateral movement of the nutrient solution through the medium. Lateral distribution of the solution also occurs along the lateral roots of the plants.

A modified re-circulating pea gravel system was constructed at California Watercress to grow baby salad greens and later mint. A greenhouse 20 ft (6 m) x 120 ft (37 m) four beds, each 4 ft (1.2 m) wide, was constructed. The irrigation system was set into the ground before covering the floor with a nursery weed mat to prevent any weed growth and to produce a sterile barrier between the underlying soil and the greenhouse environment. A closed recirculating hydroponic system was set up using a 2-in.-diameter main from a 2,500-gal (9,462-L) cistern tank. From the main 1-in.

FIGURE 7.11 Crop of tomatoes (about 6 wk old) growing in a gravel culture system.

Note: The three-way valve in the lower right corner.

FIGURE 7.12 Crop of mature tomatoes ready for harvesting.

FIGURE 7.13 Raised beds set on concrete blocks. On the left, plants in the foreground are 18 d and those in the background are 15 d. (From California Watercress, Inc., Fillmore, CA. With permission.)

submains were installed under the aisles along the length of the greenhouse. Three 0.75-in. risers entering at 40-ft (12-m) intervals of the bed length were joined to 0.75-in. black polyethylene hose having 0.25-in. tees every 12 in. (30.5 cm) along its length to supply the nutrient solution. The solution was returned to the cistern by 4-in.-diameter PVC catchment pipes placed as a collection gutter at the lower side of the beds (Figures 7.13 and 7.15). These catchment pipes joined onto a 3-in.-diameter common return pipe to the cistern.

Beds 4 ft (1.2 m) wide by 110 ft (33.5 m) long constructed of 2 in. x 4 in. treated lumber and 0.63-in.-thick plywood were set on top of 8 in. x 8 in. x 16 in. (20 cm x 20 cm x 40 cm) concrete blocks (Figure 7.14). The beds were sloped 3 in. (7.6 cm) toward the catchment pipe (across the 4-ft width). The tables were covered with a 10-mil black polyethylene liner after applying two coats of paint. A pea gravel substrate of 1.5 in. (4 cm) in depth was used as the medium.

Irrigation cycles, using a modified herb formulation as shown in Table 7.1, were repeated every 2–3 h for a 15-min period. An overhead misting system (Figure 7.15) was installed above each bed to provide adequate moisture for the germination of seeds directly sown into the beds. During germination, mist was applied every 10 min for 15 s with a mist controller. Once seedlings had fully expanded cotyledons, the mist cycles were set to every 30 min for 45 s.

After estimating the market demand, trials with many varieties of lettuce and other baby green crops were undertaken to decide on growing the following mixes in each of the beds of 100 ft x 4 ft (30.5 m x 1.2 m).

Bed 1 contained beets only, of the variety Bull's Blood. Two sowings per week of an 8-ft (2.4-m) section of bed created a cropping cycle of 6 wk. The beets were ready to harvest 3 wk after sowing and they were harvested twice before changing the crop. This provided several harvests per week, which are two 8-ft sections.

Beds 2 and 3 had lettuce mesclun mixes containing Tango (20%), Red Oak (20%), Green Romaine (20%), Red Romaine (20%), Mizuna (5%), Tah Tsai (10%), and Broadleaf Cress (5%). The cropping period for lettuce is 3 wk. Therefore, with two beds of 100 ft (30.5 m) each, the total bed length for this crop is 200 ft (61 m). Sowing twice a week gave several harvests per week on

FIGURE 7.14 Baby salad greens in beds with mist lines above. The beets in the foreground of the middle bed are 19 d and lettuce mixes 10 d in the right bed. (From California Watercress, Inc., Fillmore, CA. With permission.)

TABLE 7.1
Herb Nutrient Formulation

N	150 ppm	P	40 ppm
K	182 ppm	Ca	230 ppm
Mg	50 ppm	Fe	5 ppm
Mn	0.5 ppm	Zn	0.1 ppm
Cu	0.035 ppm	Mo	0.05 ppm
B	0.5 ppm		

a continual basis. The crop is changed after each harvest. The twice-weekly sowing schedule is as follows: six crops in the 200 ft of bed; 200/6 = 33 ft (10 m) per sowing; Tango, Red Oak, Green Romaine, Red Romaine – 6 ft 7 in. (1.25 m) each variety (20% x 33 ft); Tah Tsai – 3 ft 4 in. (1 m); Mizuna and Broadleaf Cress – 20 in. (51 cm) each.

Bed 4 contained dill (Delikat), arugula, spinach, and fennel. With one sowing per week, 3 wk per crop, and one harvest per crop, 33 ft (10 m) of bed is sown each week as follows: dill – 16 ft (4.9 m), arugula – 8 ft (2.4 m), spinach – 5 ft (1.5 m), and fennel – 4 ft (1.2 m) of bed length.

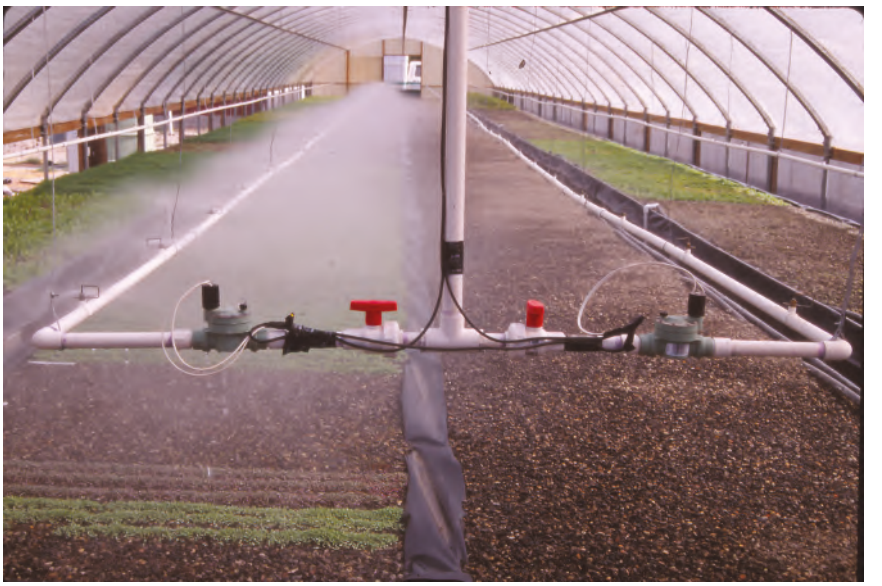

FIGURE 7.15 Mist system to assist seed germination in pea gravel beds. Note: The catchment pipe is under the poly cover at the center of the bed. (From California Watercress, Inc., Fillmore, CA. With permission.)

Plant spacing for red items is 3 in. (7.6 cm) between rows and about 0.13 in. (3 mm) between seeds within rows. For green vegetables, the spacing is 3 in. (7.6 cm) and almost touching within the rows. The wider spacing for red vegetables is to allow more light to enter the crop, which assists in producing a red color. Seed was sown by hand using a wooden stick (lathe) as a guide.

Seeds are sown directly onto the pea gravel surface and maintained moist during daylight hours by the automatic application of mist for the first 10 d. The mist provides sufficient moisture for imbibitions and subsequent growth of the seed. At the same time, it moves fine seeds into the void spaces of the gravel, protecting it from drying between misting cycles. Once the plants reach about 1-in. (2–3 cm) in height, the mist is turned off, as continued use causes white stains on the leaves because of the high calcium and magnesium carbonates in the hard water. The plants are then irrigated with the re-circulating nutrient system every 2 h for 15-min periods during daylight. At the end of the 3-wk cropping period, the plants should be no higher than 2 in. (5 cm), because if they are permitted to grow taller they become less tender with age.

Pests and disease problems associated with a short-term crop such as baby greens is less severe than with long-term crops. However, aphids, white flies, squash beetles, and various moth and butterfly larvae are common pests. These can be controlled with Pyrenone and Dipel or Xentari.

The most difficult problem was to remove the excess roots from the pea gravel between crops, as only the tops of the crop are cut with a knife. Do not use gravel culture for growing mesclun mixes when other cultures, such as the ebb-and-flood systems discussed in Section 6.9, are now available. In the ebb-and-flood system, the crop can be grown in trays or on a capillary mat, and after harvesting the capillary matting can be simply changed to reseed. Also, Section 5.6 presents a better method that can be applied for growing mesclun mixes.

Mesclun mixes are available from seed companies, already made up as mixes, so it is easier to sow as one instead of many different varieties separately and later upon harvesting mixing them. Mesclun mixes are best packaged in a ready-to-eat form that does not require washing, so a washing-packing facility of the most up-to-date standards is required.

7.5 ADVANTAGES AND DISADVANTAGES OF TRICKLE IRRIGATION

The advantages of the trickle system over the subirrigation system are:

1. Fewer problems of roots plugging the drain pipes.
2. Better aeration to the roots, since at no time are they completely submerged in water. Also, water trickles down past the roots, carrying fresh air with it.
3. Lower construction costs, since smaller nutrient tanks are needed and no valves or plenums are required.
4. A much simpler system with fewer chances of failure. Coordination of valves, and pumps, and so on, is not involved. It is simple to install, repair, and operate.
5. The nutrient solution is fed directly to each plant.

The following are some disadvantages of the system:

1. Sometimes "coning" of water movement occurs because of the relatively coarse particles of gravel. That is, water does not move laterally in the root zone but flows straight down. This results in water shortage to the plants and roots growing along the bottom of the beds where most water is present, eventually plugging drainage pipes. A subirrigation system uniformly moistens all plant roots and the medium.
2. The trickle lines sometimes get clogged or pulled out by workers. The use of filters in the main header lines will reduce clogging. The use of sweat hoses or emitters can reduce problems of workers accidentally pulling out lines.

7.6 STERILIZATION OF GRAVEL BETWEEN CROPS

The sterilization of gravel between crops can easily be done with household bleach (calcium or sodium hypochlorite) or hydrochloric (muriatic) acid used for swimming pools. A 10,000 ppm of available chlorine waste solution is made up in the nutrient tank, and the beds are flooded several times for 20 min each time. The chlorine solution is then pumped to waste, and the beds rinsed several times with clean water until all bleach residues are eliminated. The greenhouse then should be allowed to air out for 1–2 d before planting the next crop. An alternative is Zerotol, a form of hydrogen peroxide.

In a trickle system, the drain-pipe exit must be plugged to allow the beds to fill up, and the sterilizing solution can be pumped through the trickle lines. This will take time, so it is helpful to use an auxiliary pump and hose to flush the beds from above until they fill up. The same procedure is followed in rinsing the beds with clean water.

With each successive crop, some roots will remain in the medium. Over the years, chlorine sterilization will become less effective unless the roots are removed. Removal would be very costly; therefore, eventually a more powerful sterilant will have to be used, such as steam sterilization or chemicals. It is inevitable that at some point the roots will plug the drain pipes and a "snake" type rooter will have to be run through the pipes to remove them. If that does not work, the pipes will have to be dug up and cleaned before replacing them in the beds.

7.7 ADVANTAGES AND DISADVANTAGES OF GRAVEL CULTURE

Gravel culture initially is blessed with many advantages, but over time some of these advantages are lost.

The following are the advantages:

1. Uniform watering and feeding of plants.
2. Can be fully automated.
3. Gives good plant root aeration.
4. Adaptable to many types of crops.
5. Has proven to be successful on many commercial crops grown both outdoors and in greenhouses.
6. Can be used in nonarable areas where only gravel is available.
7. Efficient use of water and nutrients through a recycling system.

The following are the disadvantages:

1. Costly to construct, maintain, and repair.
2. With automatic valves, and so on, failures occur often.
3. One of the biggest problems is the root buildup in the gravel, which plugs drainage pipes. Each crop leaves some roots behind, and the moisture-holding capacity of the medium increases. Consequently, watering frequency may be reduced each year. Watering and aeration stresses occur. Over the years, this root buildup results in a graveled soil, and the advantages over a soil system will be lost. Eventually the gravel will have to be cleaned of roots, if not completely changed. Sterilization between crops by use of chlorine alone becomes ineffective.
4. Some diseases, such as *Fusarium* and *Verticillium* wilts, can spread through a cyclic system very rapidly.

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8 Sand Culture

8.1 INTRODUCTION

Sand culture was the most common form of hydroponics in areas of the world having an abundance of sand. It was particularly well suited to desert regions of the Middle East and North Africa. Now, however, nutrient film technique (NFT), rockwool, and coco coir systems have replaced sand culture because of their ability to recirculate the nutrient solution and to automatically control nutrition through the use of computerization.

Since high-quality water is rare in most of these desert locations, some form of purification through distillation or reverse osmosis (RO) is imperative for success. Recirculating hydroponic systems that efficiently utilize the costly purified water are essential from an economic standpoint.

Some of the larger sand-culture operations in the past include the following:

Superior Farming Company, Tucson, Arizona (11 acres) (4.4 ha)
Quechan Environmental Farms, Fort Yuma Indian Reservation, California (5 acres) (2 ha)
Kharg Environmental Farms, Kharg Island, Iran (2 acres) (0.8 ha)
Arid Lands Research Institute, Sadiyat, Abu Dhabi, United Arab Emirates (5 acres) (2 ha)
Sun Valley Hydroponics, Fabens, Texas (10 acres) (4 ha)

The Environmental Research Laboratory, a branch of the University of Arizona, worked with these projects. They were instrumental in proving the use of sand culture in these areas (Fontes, 1973; Hodges and Hodge, 1971; Jensen et al., 1973; Jensen and Teran, 1971).

8.2 MEDIUM CHARACTERISTICS

In Mexico and the Middle Eastern countries where greenhouse projects were established on the seacoast, the normal beach sand was used as the medium (Jensen and Hicks, 1973; Massey and Kamal, 1974). Once the growing medium (sand) was leached free of excess salts, vegetables were either seeded directly in the sand or planted as transplants. In the US Southwest, concrete river-wash sand is used, not mortar sand, as it is too fine and will puddle. Puddling is indicated by water coming to the surface on vibration of the sand. It is a result of a high percentage of silt and fine sand. The aggregate must be washed free of fine silt and clay. It should also be relatively free of particles of diameter over 0.0625 in. (2 mm) and under 0.025 in. (0.6 mm). A properly screened sand-culture aggregate will drain freely and not puddle after application of a large amount of water.

Aggregates that are soft and tend to disintegrate should be avoided. However, it may not be possible to avoid using soft particles in areas where only limestone sand is available. In such cases, nutrients should be added and the *p*H adjusted daily, as discussed in Chapter 7.

8.3 STRUCTURAL DETAILS

Two methods of utilizing sand as a growing medium have proven satisfactory. One is the use of plastic-lined beds; the other involves spreading sand over the entire greenhouse floor.

DOI: 10.1201/9781003133254-8

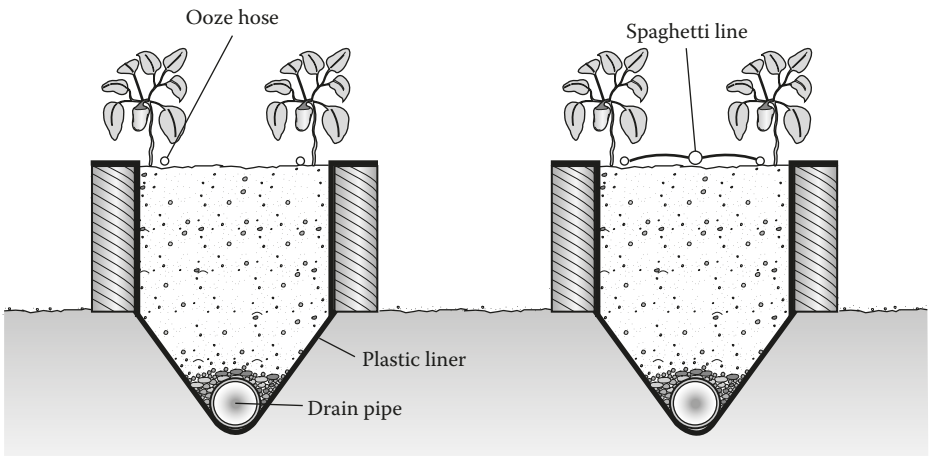

FIGURE 8.1 Cross section of sand-culture beds. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

8.3.1 Beds with Plastic Liner

Growing beds may be built as above-ground troughs with wooden sides (Figure 8.1) similar to those described for gravel culture in Chapter 7. Six-mil black polyethylene can be used for the liner, but 20-mil vinyl is more durable. The bottom of the trough should have a slight slope of 6 in. (15 cm) per 200 ft (61 m), so that it can be drained or leached when necessary. The drain pipe should be placed in the entire length of the bed. A 2-in. (5-cm)-diameter pipe is large enough, since in sand culture only excess solution (about 10% of that added) is drained. Connect the drain pipes from all beds to a main at one end, which collects the waste water and conducts it away from the greenhouses.

Similar to gravel culture, drainage holes are crosscut with a saw one-third the distance through the pipe every 18 in. (46 cm). The cuts must be against the bottom of the bed so that plant roots are discouraged from entering the pipes. As in gravel culture, one end of each pipe should be left above the ground so that a Roto-Rooter can be used to clean them. An alternative to making these drain pipes, which is very laborious, is to purchase the black-coiled plastic drainage pipe from an irrigation supplier. This drain pipe is pre-punched with holes.

The width of the beds may be 24–30 in. (61–76 cm) and the depth 12–16 in. (30.5–40.6 cm). The bottom of the bed may be level, round, or V-shaped with the drainage pipe in the middle.

8.3.2 Greenhouse Floors Lined with Polyethylene

Construction costs can be reduced in areas where lumber is expensive or difficult to obtain by lining the greenhouse floor with black 6-mil polyethylene and filling it with 12–16 in. (30.5–40.6 cm) of sand (Jensen, 1971). The floor should have a slight grade of 6 in. (15 cm) per 100 ft (30.5 m), so that the area may be drained or leached when necessary. Generally, two layers of 6-mil plastic are used to cover the entire floor.

Before installing the polyethylene, the floor should be graded and packed. Polyethylene sheets should be overlapped several feet (0.6 m) when more than one sheet is required in wide houses. The drain pipe, 1.25–2 in. (3.1–5 cm) in diameter, or black drainage pipe as mention above, is then placed on top of the polyethylene at a uniform spacing of 4–6 ft (1.2–1.8 m) between pipes, depending on the nature of the sand. The finer the particles, the closer the pipes will have to be spaced. These drain lines must run parallel to the slope down into a main drain running across the low end of the greenhouse grade. Once the drain pipes are in place, sand is spread over the entire area to a depth of 12 in. (30.5 cm) (Figures 8.2 through 8.4).

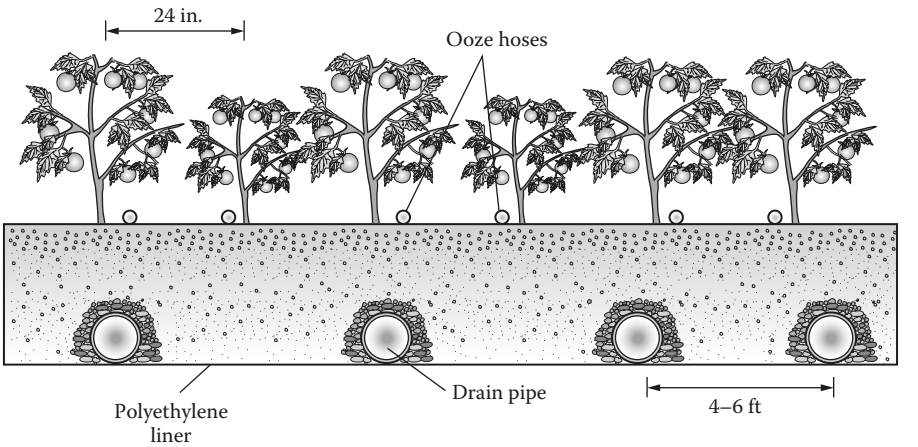

FIGURE 8.2 Cross section of greenhouse floor design for sand culture. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 8.3 The laying of a polyethylene liner and drain pipes.

If the medium is spread shallower than 12 in. (30.5 cm), there will be a problem in obtaining uniform moisture conditions and a greater chance of roots growing into the drain pipes. The surface of the bed should be graded to the same slope as the floor.

8.4 DRIP (TRICKLE) IRRIGATION SYSTEM

A drip irrigation system must be used with sand culture. Waste nutrients (approximately 10% of that applied) are not recycled. Such a system is termed an *open system*, as opposed to the recycled or closed system of gravel culture. The drip irrigation system feeds each plant individually by use of emitters and drip feed lines, or sweat (ooze) hoses (Figure 8.5).

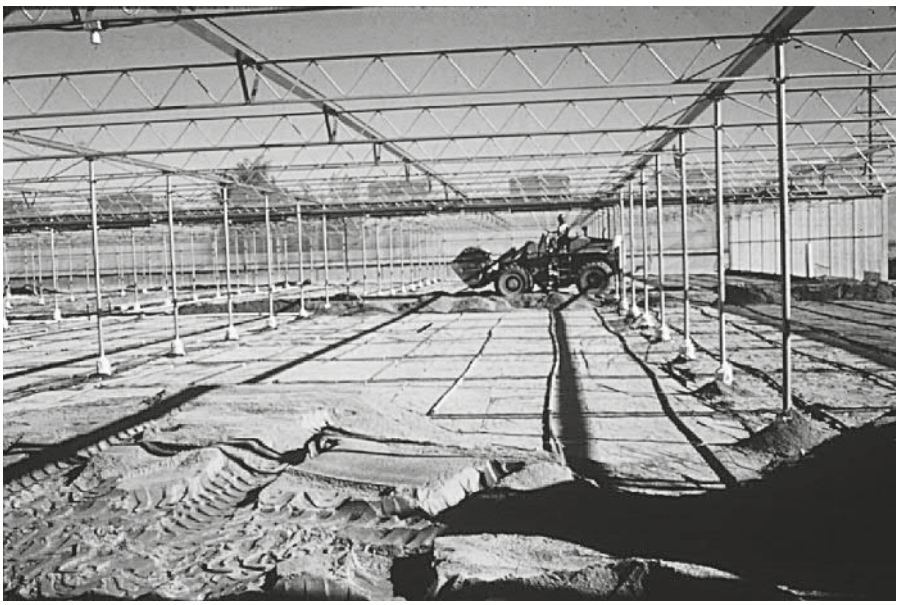

FIGURE 8.4 Back filling with 12 in. of sand.

FIGURE 8.5 The installation of ooze hoses for an automated drip irrigation feeding system

If ooze hose is used, 4-in. (10-cm) spacing between outlets is recommended. If the surface of the bed is level, the tube should not be over 50 ft (15 m) long. If the surface is sloped 6 in. (15 cm), the tube can be 100 ft (30.5 m) long, with the supply manifold at the high end.

On a level bed, the supply manifold may run down the center of a 100-ft (30.5-m) bed, with 50-ft (15-m) lines off either side. The objective of a greenhouse drip irrigation system is to apply uniform water at optimum levels to all plants.

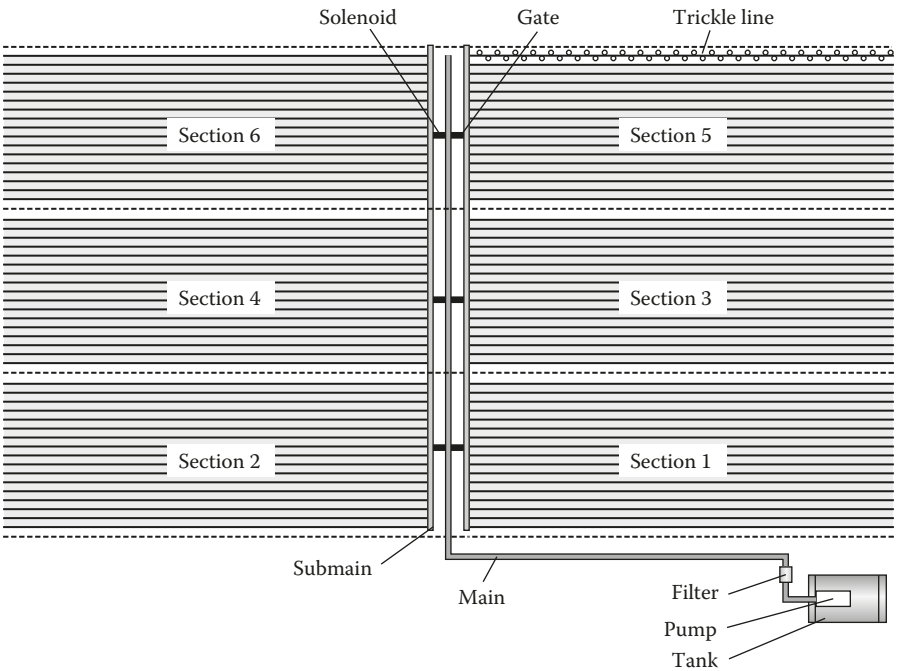

FIGURE 8.6 A typical drip (trickle) irrigation system. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

8.4.1 Planning a Drip Irrigation System

Divide the total greenhouse area into equal or similar crop sections or into individual houses. Plan irrigation systems so that each house or section can be irrigated independently (Figure 8.6). Piping to each section should be capable of distributing 1.6–2.4 gal/min (6–9 L/min) for each 1,000 ft^2 (93 m^2), or 8–12 gal/min (30–45 L/min) for each 5,000 ft^2 (465 m^2) of growing area.

The rate and duration of each irrigation cycle will be a function of the type of plant, its maturity, weather conditions, and time of day. In all cases, a tensiometer system should be set up so that no more than 8–10% of the nutrient solution applied at any irrigation cycle is wasted. This can be determined by measuring the amount of water passing through the main supply line and that flowing out of the main collector drain line.

The volume of water that can enter each greenhouse section should be regulated by a flow-control valve that is sized and selected according to plant water requirements of that greenhouse section. Flow valves are usually available in 1- and 2-gal/min (3.8- and 7.6-L/min) size increments and fit 0.75- and 1-in. (1.9- and 2.5-cm) pipe connections. The flow valve should be located upstream from the solenoid valve where the irrigation cycle is automatically controlled. While a minimum water supply pressure of 15 psi (pounds per square inch) (103.5 kiloPascals or kPa) is required for proper operation of most flow-control valves, for best performance the main water supply line should be maintained at a pressure between 20 and 40 psi (138 and 276 kPa). The flow-control valve assures a constant quantity of water and reduces water pressure in the irrigation system piping to 2–4 psi (13.8–27.6 kPa), which is optimum for low-pressure drip irrigation emitters.

The main line piping should be 2- to 3-in. (5- to 7.5-cm)-diameter PVC, depending on the area of the largest greenhouse section or number of sections watered at any one time. Since all sections are not irrigated at the same time, the total volume capacity of the main line needs to satisfy only

FIGURE 8.7 Automatic proportioner fertilizer-injector system.

the maximum number of sections operating at a time. Header lines should be 1-in. (2.5-cm)-diameter PVC pipe for a 5,000-ft^2 (465-m^2) section. Larger sections should use a larger pipe. The header line is connected to the main line with a tee at its center to equally divide the water supply (Figure 8.6). A gate valve with a solenoid valve downstream on this connection between the main and submain (header) operates the irrigation cycle. From this header line, a 0.5-in. black polyethylene pipe is run along the inside of each plant row. The emitters are placed in these lateral lines at the base of each plant. Flexible polyethylene pipe (usually 80–100 psi) is normally used for these emitter laterals. Where manufactured emitters are used, a 0.5-in. pipe will provide equal water distribution and uniform water application throughout 100- to 150-ft (30.5- to 46-m) greenhouse irrigation runs.

Most drip emitters can deliver water at a rate of 0.5–3 gal/h (2–11 L/h), depending on the water pressure in the lateral line. A greenhouse drip-irrigation system should be designed so that each emitter applies 1–1.5 gal/h (4–6 L/h).

While spaghetti tubing is more economical than manufactured emitters, more labor is required for its installation and maintenance. Perforated (ooze) hose is installed more easily but is not as durable (it usually must be replaced between crops).

Emitters, pipes, and fittings should be black to prevent algae growth inside the piping system.

Water must be filtered before flowing into a drip irrigation system. Y-type, in-line strainers, containing at least 100 mesh screens and equipped with clean-out faucets, should be installed with the screen housing and flush valve down. The filter(s) should be installed downstream from the fertilizer injector in the main supply line. It is wise to also install a filter in the main supply line upstream from the fertilizer injector.

The fertilizer injector or proportioner automatically proportions the right amount of stock solution into the main supply line during every irrigation cycle. Positive-displacement pump injectors, venturi proportioners, and forced-flow batch tanks are some of the types of fertilizer injectors available commercially (Figure 8.7).

Alternatively, a nutrient solution can be pumped into the drip irrigation system directly from a large storage tank. Today most growers use injectors and stock solution tanks.

Irrigation is now controlled by the use of sensors with a feedback system to a central computer. These control the solenoid valves and the activation of the fertilizer injector or tank pump, which allow one section of the greenhouse to be irrigated at one time.

If calcareous sand is used, the amount of chelated iron going to the plants must be increased, as discussed earlier. When fertilizer proportioners are used, two stock solutions are prepared. One is a calcium nitrate and iron solution and the other contains magnesium sulfate, monopotassium phosphate, potassium nitrate, potassium sulfate, and the micronutrients. The proportioner must be a twin-head type. For example, if each head injects 1 gal (3.785 L) of stock solution into each 200 gal (757 L) of water passing through the water line, then the stock solution will be 200 times the final concentration that reaches the plants. In this case, the proportioners would have a ratio of 1:200. Two manufacturers of proportioners in the United States are Anderson and Smith.

8.5 WATERING

If a time clock is used, water the crop two to five times per day, depending on the age of the plants, weather, and time of the year. As mentioned earlier, enough water is added during each cycle to allow 8–10% of the water applied to drain off. Twice a week a sample of this drainage should be tested for total dissolved salts (TDS). If the TDS reaches 2,000 ppm, the entire bed should be leached free of salts by using pure water. However, if no extraneous salts such as sodium are found, pure water may be irrigated onto the crop until the plants themselves, over a few days, lower the salt level down to a point at which nutrients can again be added to the irrigation water.

When using a proportioner, the TDS of the nutrient solution going to the plants should be checked daily to be sure that the injector is functioning properly. Most injector systems have a *p*H and electrical conductivity (EC) meter in the main line, so monitoring is automatic. Also, check whether each injector pump is injecting the proper amount of stock solution to the irrigation water.

If a nutrient tank is used to store the nutrient solution, it must be large enough to supply water to all the plants in the greenhouse for at least 1 wk. Its size therefore will depend on the total greenhouse area. If several crops having very different nutrient requirements are grown, two storage tanks should be used, each having its specific formulation suitable to the crop it is feeding. The entire irrigation system connected to one tank must be independent of the other.

Since a sand-culture system is an open system in which excess nutrient solution goes to waste, there will be little change in the formulation of the nutrient solution in the storage tank. The *p*H, however, should be checked daily, especially in areas having highly alkaline waters.

The nutrient solution in the storage tank does not have to be changed regularly as was necessary in gravel culture. The tank need only be cleaned periodically of any sludge and sediment due to inert carriers in the fertilizer salts. To help prevent this, use some type of agitation or aeration of the solution in the tank. Make up a new batch when the existing solution is almost depleted.

Fertilizer injectors have several advantages over a storage tank: (1) they require less space and (2) they are capable of making rapid changes in the nutrient solution formulation to compensate for changes in plant requirement under changing weather conditions. For instance, during a period of dull weather, the concentration of nitrogen can be easily reduced, whereas in a storage-tank system the entire volume of nutrient would have to be altered.

8.6 STERILIZATION OF SAND BEDS BETWEEN CROPS

The best method of eliminating diseases and nematodes in the sand is to use steam sterilization. If the greenhouse is heated with a hot water boiler, the boiler should be assembled with a steam converter, which can produce sufficient steam for sterilization (pasteurization) of the growing beds. The

steam may be put through the drain system provided the drain lines will not be damaged by the high temperature. Alternatively, pipes can be placed within the top few inches of the sand and the beds covered with heavy canvas or polyethylene before releasing the steam. Pipes are moved along the beds as sterilization is completed for each section of the bed.

8.7 SAND CULTURE OF HERBS

Chives, basil, sage, and mint have been grown successfully in sand-culture beds at California Watercress, Inc., Fillmore, California. In one greenhouse of dimensions 30 ft x 156 ft (9 m x 47.5 m), 17 beds 8 ft x 12 ft (2.4 m x 3.65 m) on one side and 17 beds 8 ft x 14 ft (2.4 m x 4.27 m) on the other side were constructed using 1 in. x 6 in. treated lumber. The 6- to 8-in. (15- to 20-cm)-deep beds were lined with 6-mil black polyethylene. The bottoms of the beds were sloped 2 in. (5 cm) from one side to the other to assist in drainage.

At a second location, a greenhouse of one-half acre (0.2 ha) was erected to grow herbs. In that greenhouse, one range 30 ft x 165 ft (9 m x 50 m) was used to grow sage and mint in sand. Before building the beds, the irrigation system was installed. A 2-in. PVC main with a 0.75-in. riser to each bed was set in place. A solenoid valve on the main line operated by an irrigation controller activated the feeding cycles from an injector system.

The entire floor of the greenhouse was covered with a nursery weed mat to prevent weed growth (Figure 8.8). The underlying soil was very sandy with many rocks, which provided excellent drainage. The beds, of the same dimensions as in the other greenhouse, were placed on top of the weed matting and staked in position. However, unlike the other beds, these were not lined with polyethylene. The treated boards making up the beds were simply set on top of the weed-mat covering, as the weed mat allows water to move through it freely while roots cannot easily penetrate.

A coarse river-wash sand of granitic origin was used as the medium. In the larger greenhouse, the beds of sand were covered with 1 in. (2.5 cm) of peat-perlite mix to improve lateral movement of the solution. It was found later that the sand had too much silt in it as crusting occurred with the hard

FIGURE 8.8 Greenhouse floor covered with a weed mat. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 8.9 Drip irrigation system of sand-culture beds growing herbs. (From California Watercress, Inc., Fillmore, CA. With permission.)

water of the area. To improve the sand, approximately one-third was removed and replaced with the peat-perlite mix, which was incorporated in the sand. The other beds in the smaller greenhouse had a better quality of sand from a different source, and chives and basil grew well.

Drip irrigation lines were placed along the length of the beds from the 0.75-in. header at 12-in. (30.5-cm) centers (Figure 8.9). "T-tape" having small holes every 12 in. (30.5 cm) provided 38 gph (gallons per hour) per 100 ft at 10 psi pressure, which is equivalent to 144 L/h per 30.5 m at 69 kPa pressure. The T-tape was secured with an adapter attached to a 0.25-in. black poly drip emitter line, which in turn was inserted into the 0.75-inch header via a hole and sealed with silicone rubber (Figure 8.10). The ends of the T-tape were sealed, folding them several times and taping them with pipe tape.

Sage was seeded in a peat-lite medium in 98-celled trays and later transplanted to the beds (Figure 8.11). Mint cuttings were rooted in 2.25-in. x 3-in. deep (6 cm x 7.5 cm) plastic pots with a peat-lite medium before transplanting. Chives were transplanted from the field after washing the soil from their roots. The basil was grown from seed.

The mint was ready for first harvest after 6 wk (Figure 8.12), with continued harvests every 4–5 wk depending on the season. The basil was harvested every 3 wk. Chives were harvested on a 30- to 35-d cycle depending on day length and light conditions (Figures 8.13 through 8.15). Two to four beds were cut each day over a 2-wk harvesting period. These herbs are bundled with elastic bands or twist ties and sold as dozens of bunches.

8.8 ADVANTAGES AND DISADVANTAGES OF SAND CULTURE

Advantages of sand culture over gravel culture are as follows:

1. It is an open system, that is, the nutrient solution is not recycled, and so the chances of diseases such as *Fusarium* or *Verticillium* spreading in the medium are greatly reduced.
2. There are fewer problems with drain pipes getting plugged with roots since the denser medium of sand favors lateral root growth.

FIGURE 8.10 Attaching T-tape drip line to poly tube adapter. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 8.11 Transplanting sage into sand-culture beds. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 8.12 Sage 10 wk old (left beds) and mint 5 wk after transplanting (right beds). (From California Watercress, Inc., Fillmore, CA. With permission.)

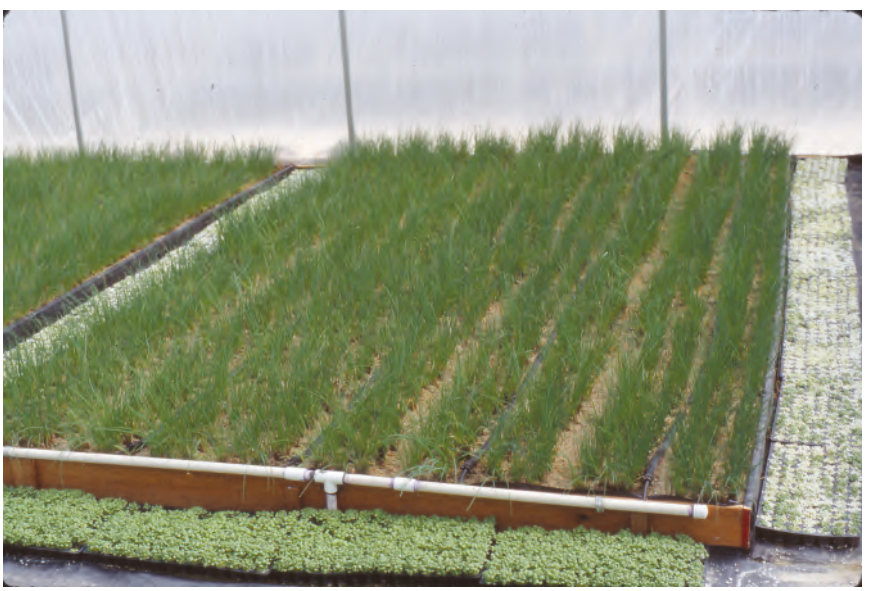

FIGURE 8.13 Chives 7 d after harvesting. (From California Watercress, Inc., Fillmore, CA. With permission.)

3. The finer sand particles allow lateral movement of water through capillary action so that solution applied at each plant becomes evenly distributed throughout the root zone.
4. With the right choice of sand combined with a drip irrigation system, adequate root aeration is achieved.
5. Each plant is fed individually with a new complete nutrient solution during each irrigation cycle – no nutrient imbalance occurs.

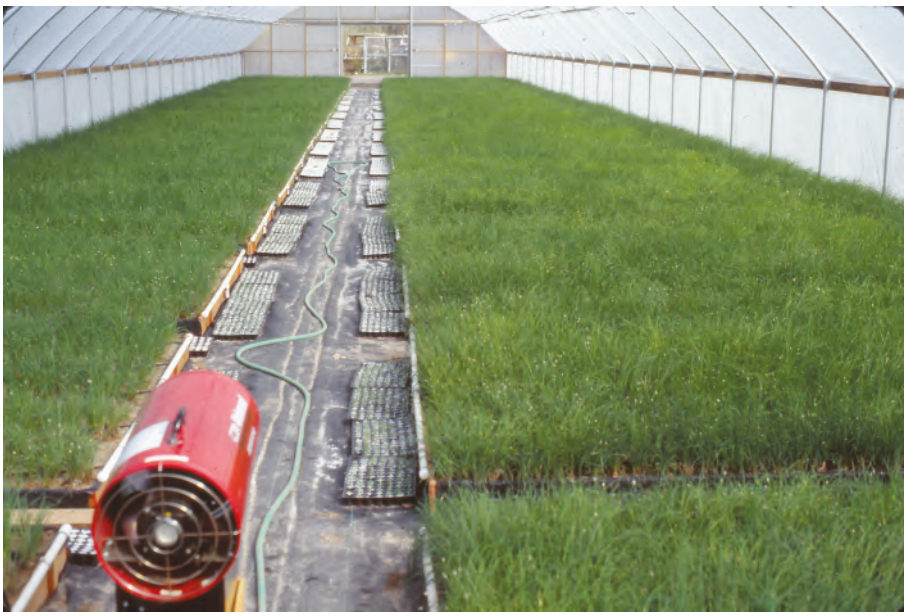

FIGURE 8.14 Chives 33 d after cutting, ready for another harvest. Note: The space heater in the foreground. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 8.15 Chives just harvested on the right. Remaining beds on the right are ready to harvest at 23–25 d after a previous harvest. Beds on the left from front to back are 2–4 d after harvesting. (Courtesy of California Watercress, Inc., Fillmore, CA. With permission.)

6. Construction costs are lower than for a subirrigation gravel system.
7. The system is simpler, easier to maintain and service, and more foolproof than a subirrigation gravel-culture system.
8. Owing to the smaller particle size of sand, water retention is high, and only a few irrigations are required each day. If a failure occurs, there is more time available to repair the system before the plants will use up the existing water in the medium and begin to experience water stress.
9. Smaller, centrally located nutrient reservoirs or injectors can be constructed away from the actual growing area of the greenhouse.
10. Sand is readily available in most locations. When using calcareous sand, the formulation can be adjusted to compensate for daily *p*H changes and shortages of iron and/or other elements.

Disadvantages of sand culture compared with gravel culture are as follows:

1. One of the major disadvantages is that either chemical or steam sterilization methods must be used to fumigate between crops. However, such methods are thorough, even if they are a little more time consuming than the use of bleach with gravel culture.
2. Drip irrigation lines can become plugged with sediment. This, however, can be overcome by the use of in-line 100- to 200-mesh filters, which can be easily cleaned daily.
3. Some claims are made that sand culture uses more fertilizer and water than a cyclic gravel-culture system. Again, this can be overcome by good management. The waste should be monitored and feeding adjusted so that no more than 7–8% of the solution added is actually drained out. Even in gravel culture, the waste can be equally as great, if not greater, because of the need to change the nutrient solution periodically.
4. Salt buildup may occur in the sand during the growing period. This can be corrected, however, by flushing the medium periodically with pure water. Again, proper management with monitoring of salt accumulation from the drainage water is important to prevent excess salt problems.

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9 Sawdust Culture

9.1 INTRODUCTION

Sawdust culture was particularly popular during the early introduction of soilless culture in the 1970s in British Columbia, Canada. This was due to the large forest industry in the West Coast of Canada and the Pacific Northwest of the United States. Sawdust was, at that time, a waste material of sawmills and was burnt to dispose of it. The sawdust had no value and could be obtained from sawmills for the cost of trucking it to the greenhouse site. In British Columbia, Canada, the Canada Department of Agriculture Research Station at Saanichton carried out extensive research for a number of years to develop a sawdust-culture system for greenhouse crops (Maas and Adamson, 1971; Mason and Adamson, 1973). The need for a soilless-culture system became evident with increased soilborne nematode infestations and diseases coupled with poor soil structure, which made the profits from greenhouse crops very marginal. Over the next few decades in British Columbia, over 90% of all greenhouses used some form of soilless culture for vegetable and flower production. Vegetable growers usually used sawdust culture, while flower producers used a peat-sand-perlite mixture.

Sawdust culture began to decline in the early 1980s as rockwool culture was introduced. Today, very few, if any, growers still use sawdust culture, as now sawdust is used as a byproduct in making fiber-board products used in house and furniture construction. As a result, it is no longer a cheap substrate, if at all available.

9.2 GROWING MEDIUM

Sawdust was adopted as a growing medium in the coastal region of British Columbia because of its low cost, light weight, and availability. Moderately fine sawdust or one with a good proportion of planer shavings is preferred, because moisture spreads better laterally through these than in coarse sawdust.

Sawdust from Douglas fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) were found to give best results (Maas and Adamson, 1971). Western red cedar (*Thuja plicata*) is toxic and should never be used.

While other media such as sphagnum peat, ground fir bark, and mixtures of sawdust with sand and/or peat were tested successfully, they are more expensive and therefore might be used if sawdust is unavailable.

One precaution that should be taken with sawdust is that of determining its sodium chloride content. Logs are floated in barges on the ocean and often remain in the water for many months before going to a sawmill. They absorb sea water over this time and thus acquire salt (sodium chloride) levels toxic to plants. Therefore, as soon as the sawdust is received, samples should be taken and the sodium chloride content tested. If any significant amount of sodium chloride is found (greater than 10 ppm), the sawdust should be thoroughly leached with pure fresh water once it is placed in the beds, but before planting. This leaching process may take up to a week in order to reduce the sodium chloride to an acceptable level.

9.3 BED SYSTEM

The growing beds are usually constructed of rough cedar and lined with 6-mil black polyethylene or 20-mil vinyl similar to those designs under sand culture (Figure 9.1). Rough cedar boards 1 in. x

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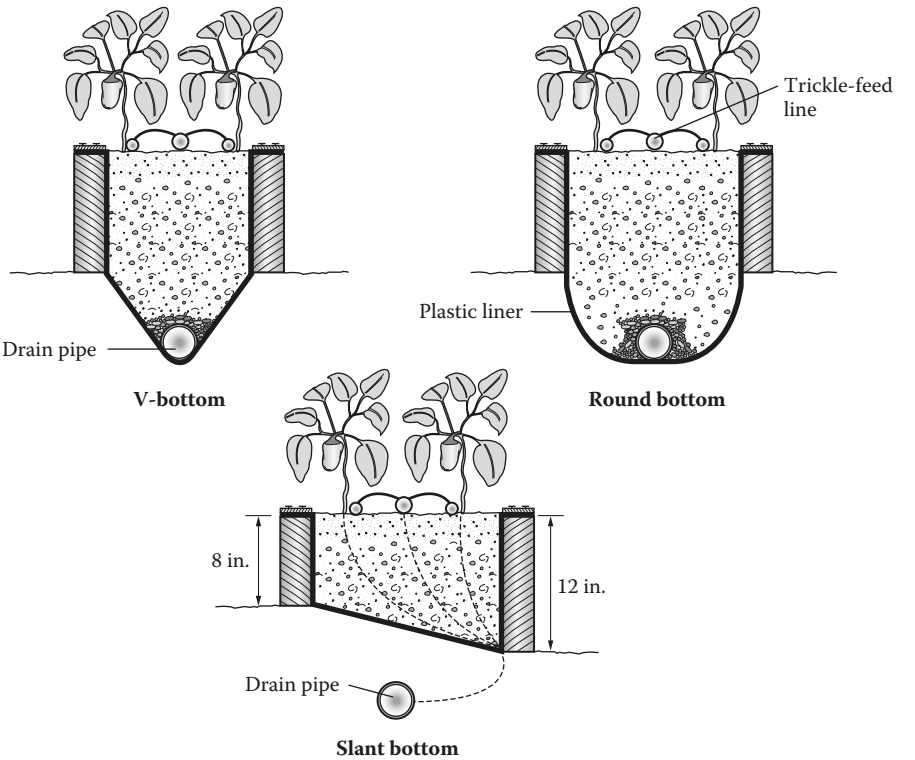

FIGURE 9.1 Cross sections of sawdust-culture beds. (Courtesy of George Barile, Accurate, Inc., Holbrook, NY.)

8 in. (2.5 by 20 cm) can be used for the sides. Either a V-bottom or round-bottom bed configuration is suitable (Figure 9.1). The depth of the beds should be 10–12 in. (25–30.5 cm). A 2-in. (5-cm) diameter drain pipe is placed on the bottom of the bed.

Beds are usually 24 in. (61 cm) wide; however, 20-in. (51-cm)-wide beds (inside dimension) are adequate with 32-in. (81-cm) pathways between the beds. Studies by Maas and Adamson (1971) have shown that even somewhat narrower and shallower beds, with a volume of 0.33 ft^3 (0.009 m^3) of medium per plant, are satisfactory. If narrower beds are used, the pathways should be widened to provide the same total amount of greenhouse area for each plant, as light requirements for the plants are the same regardless of the ability of the volume of medium required to provide adequate nutrition.

An alternative to these standard bed designs is the use of sloped-bottom beds (Figure 9.1). In this case, the beds are constructed of rough cedar 1 in. x 8 in. (2.5 x 20 cm) on one side and 1 in. x 12 in. (2.5 x 30.5 cm) on the other side. The 1 in. x 12 in. lumber is covered with the liner on the inside face and around the top and bottom edges. The 1 in. x 8 in. lumber is cover with the liner on one face and extends on a slope toward the wide side. But a small gap (0.25 in.) (0.6 cm) between the end of the poly liner and the wide side allows drainage of excess solution to a drainage pipe located several feet (61 cm) below the beds (Figure 9.1).

Drain pipes are installed when the site is leveled before the construction of the greenhouse. In this case, a standard perforated plastic drain pipe is used. It is placed in a ditch dug by an automatic ditch-digging machine (Ditch Witch). When a fine-texture (clay loam) soil is present, a filtering material (binding) placed above and around the pipe will prevent clogging of the holes in the pipe

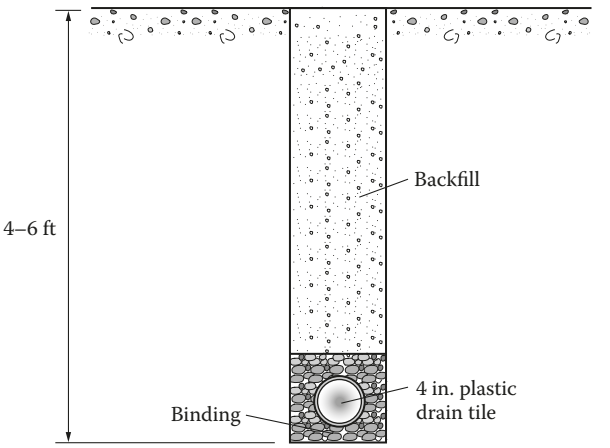

FIGURE 9.2 Cross section of a drainage ditch and 4-in. perforated drain pipe. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

(Figure 9.2). The best material is a composition of varied particle sizes: coarse sand to fine sand, pea gravel. The material should be placed to a depth of approximately 6–8 in. (15–20 cm) above and around the tile.

9.4 BAG SYSTEM

The most common system is to use long plastic bags similar to those of rockwool slabs. These are correctly termed *slabs*. The slabs are made from 6-mil thick white-on-black polyethylene "layflat" plastic, which is heat sealed on one end. They are filled with the medium using a hopper and chute that fits into the top of the bags. Once filled, the other end of the bags is closed with a heat-sealing machine. The process can be fully mechanized to reduce labor. Finished bags measure approximately 8–10 in. (20–25 cm) wide by 3 ft (90 cm) long by 3–4 in. (8–10 cm) thick, as shown in Figure 9.3. Up to six tomato plants may be grown in one bag.

Seedlings are started in rockwool cubes, which are transplanted into rockwool blocks, which are then placed into the sawdust bags, similar to rockwool culture. For an early crop (crops seeded by mid-December), the growing blocks are placed on top of the sawdust bags, but not allowed to root out until one flower truss sets fruit. Then holes are cut below the blocks in the plastic bag and the blocks set into the holes.

In British Columbia, where light is limited during the winter months, when tomato seedlings are started it is advisable to use high-intensity discharge (HID) 400-W sodium vapor lights to give 5,500 lx (510 ft-c) intensity at plant surface with a 20-h photoperiod. Seedlings should be grown under this propagation section of the greenhouse until they are ready for transplanting into the bags. Seedlings are generally sown in mid-December and transplanted in mid-January.

The greenhouse floor is lined with white polyethylene to prevent contact of the roots growing from the bags with the underlying soil. The white polyethylene also serves to reflect light (much needed during the winter months) and seal out any insect and disease organisms present in the underlying soil. Similar to rockwool culture, the floor is sloped to create a swale between each set of two rows of bags for drainage of excess solution out of the greenhouse. Hot water heating pipes conducting heat from a central boiler are laid in the aisles between the double rows of bags (Figure 9.4). The heating pipes also serve as a track for a mobile harvesting plant maintenance cart to run on (Figure 9.5).

FIGURE 9.3 Sawdust slabs with six plants. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 9.4 Sawdust culture with hot water heating pipes and carbon dioxide tube next to left pipe. (From Gipaanda Greenhouses Ltd., Delta, B.C., Canada. With permission.)

FIGURE 9.5 Mobile harvesting working cart runs on heating pipes. (From Houweling's Group, Camarillo, CA. With permission.)

Each plant is fed individually using a spaghetti trickle-feed line placed on the rockwool block in the sawdust bag. The irrigation line runs the length of the rows along one side of the slabs (Figure 9.6). The nutrient solution is pumped from a central injector system using stock solution tanks. Carbon dioxide enrichment is also distributed to the plants by a small polyethylene conduction tube running the length of the rows next to the irrigation line (Figures 9.4 and 9.6). The carbon dioxide is generated as a by-product of combustion of natural gas from the central boilers and is piped to each greenhouse (Figure 9.7).

Tomatoes are harvested into 25-lb (11-kg) plastic tote bins using the mobile carts running on the heating pipes, and, with tomato on vines (TOVs), are boxed in the greenhouse (Figures 9.8 and 9.9). Activities such as pollination, suckering, and tying string supports, are made easier by use of a mechanically raised platform running on the heating pipes, as shown in Figure 9.5. Harvested tomatoes in tote bins or boxes are moved using a pallet jack, fork lift, or trailers pulled by a tractor (Figure 9.9).

With the sawdust-culture system in British Columbia, generally one crop of tomatoes a year is grown. Seeding is in mid-December, with production beginning by late March and continuing until November.

Many northern US and Canadian growers have now established subsidiary operations in the southwestern United States. Houweling's Group located in Camarillo, California, constructed 20 acres (8 ha) by 1997 and has continued to expand to a total of 126 acres (50 ha) by 2009. More on this operation is discussed in Chapters 10 and 11.

FIGURE 9.6 Sawdust culture with drip irrigation lines and heating pipes. Note: The CO_2 poly line next to the drip line. (From Houweling's Group, Camarillo, CA. With permission.)

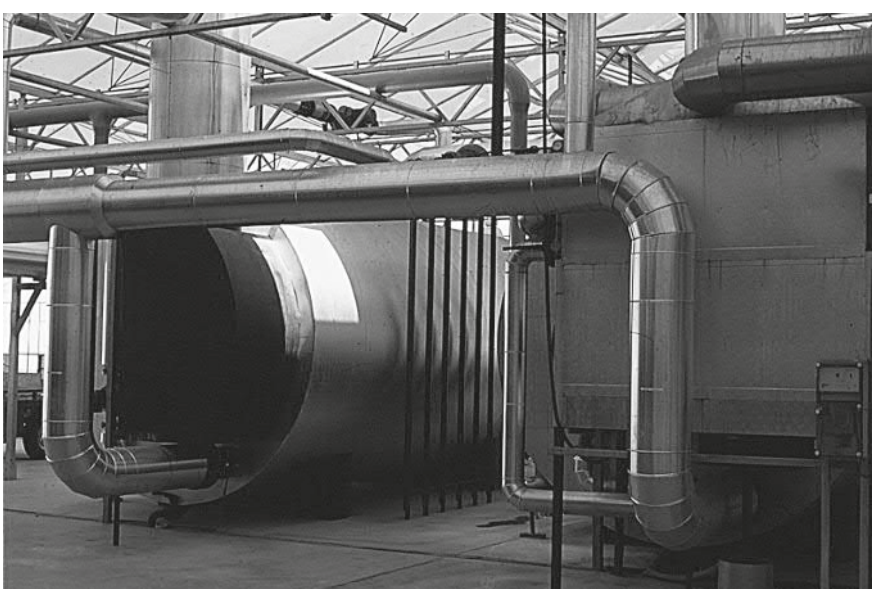

FIGURE 9.7 Carbon dioxide recovery unit attached to central boiler.

FIGURE 9.8 Tomatoes are harvested into plastic tote bins. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 9.9 A tractor with carts transports the harvested product. (From Eurofresh Farms, Wilcox, AZ. With permission.)

They grew tomatoes in the first year in a foam substrate set up similar to rockwool and sawdust cultures using a drip irrigation system. Problems with nonuniform distribution of moisture in the foam slabs prompted them to return to their conventional sawdust culture. On expansion, they turned to growing a large percentage of TOV using the variety Tradiro.

This southern location enables the greenhouse company to focus on winter production when prices are highest and their Canadian operation has less or no production. Tomatoes are seeded in July and transplanted in August to begin production by October. Harvesting takes place until June.

FIGURE 9.10 Sawdust slabs shipped from Canada. (From Houweling's Group, Camarillo, CA. With permission.)

Sawdust-filled slabs (bags) similar in dimensions to rockwool slabs are transported from Canada (Figure 9.10). Before setting out the slabs, the floor is covered with a 6-mil white-on-black polyethylene barrier to prevent contact of plant roots with the underlying substrate (Figure 9.11). The slabs are 8 in. (20 cm) wide by 3 in. (7.5 cm) thick by 39 in. (1 m) long. Seed is sown in rockwool cubes, which after several weeks are transplanted to large rockwool blocks (double blocks) 6 in. x 3 in. x 2.5 in. (15 x 7.5 x 6.5 cm) (length x width x height). Two seedlings are transplanted per double block. Many growers buy their seedlings from a specialized transplant grower such as Bevo Agro as mentioned in Chapter 6. The transplants are set into the slabs when they are 4–5 wk old, about 6 in. (15 cm) high (Figure 9.12). Each slab contains six plants that are trained in a V-cordon fashion strung alternatively to overhead support wires (Figure 9.13). V-cordon training also makes more light available for intercropping a young crop between the rows.

Each plant is irrigated with a drip line secured by a small stake. Several slits are cut in the polyethylene wrapper of each slab to permit good drainage. The drainage (leachate) flows to the underground drainage pipes through slits in the ground cover.

9.5 NUTRIENT SOLUTION DISTRIBUTION SYSTEM

In both the bed and bag systems of sawdust culture, a drip irrigation system is used to supply the water and nutrient requirements of the plants. As pointed out in Chapter 8, adequately sized main headers and valves are needed to balance the flow to the row headers. Row headers are usually made of 0.75 in. plastic black poly hose, which can handle 200 (1.66 mm diameter) feeding tubes. Row headers of 0.5- and 1-in. sizes can supply 100 and 300 feeding tubes, respectively. The trickle lines are attached to the black poly headers with 0.5-gal/h (2-L/h) flow rate compensating emitters.

Plants are supplied with nutrient solution directly from a dilute-solution storage tank or through a fertilizer proportioner from containers of concentrated stock solutions as described for sand culture (Section 8.4). The dilute-solution system needs a storage tank, a pump, filters, and a distribution system.

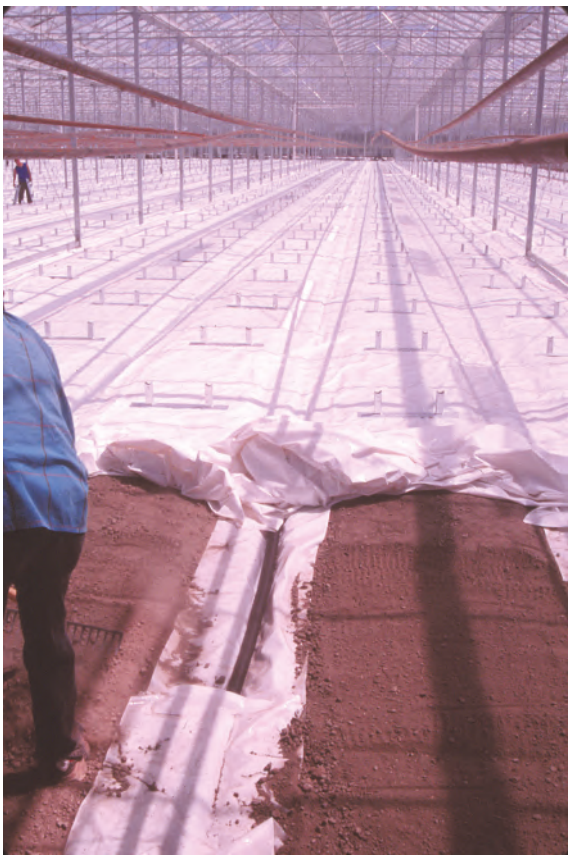

FIGURE 9.11 White-on-black polyethylene floor barrier. Note: The drainage pipe under the polyethylene floor barrier located in what will be the middle of the plant rows. Also, the heating pipes are temporarily hung above before placing them on the pipe supports on top of the liner. (From Houweling's Group, Camarillo, CA. With permission.)

Determine the capacity of the tank from the number of plants to be fed at one time. The tank should be able to supply at least 1 qt (1 L) of solution per feeding for each plant for total feeding requirements for 1 wk. The total volume needed depends on the number of irrigation cycles required, which in turn is a function of weather conditions, plant maturity, and the nature of the plant. Some growers install more than one tank so that they can prepare the nutrient solution at least a day in advance of the estimated time of depletion of the other tank. In this way, the recently made nutrient solution can be heated for at least 12 h by an immersion heater to bring its temperature to an optimum level of 65–70°F (18–21°C) before it is applied to the plants.

This system of using regular-strength nutrient solution in large storage tanks has now given way to the use of stock solutions and injectors as was described in Chapter 3. With stock solutions, large plastic storage tanks are also used. The tanks and injection system should be located in header houses near water supply and have close access to fertilizers.

The distribution system consists of a main supply line, submain headers, laterals, and drip lines with emitters, fittings, and controls (Figure 8.6). Gate valves and solenoid valves should be installed in the submain lines so that there is the option of controlling the feed supply to each greenhouse section. In this way, the flow to each section can be varied if there are differences in the volume requirements of the plants. The submain header is connected to the main header and located

FIGURE 9.12 Transplants are set onto sawdust slabs. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 9.13 V-cordon training system of tomato-on-vines (TOV). Note: The young intercrop plants. (From Houweling's Group, Camarillo, CA. With permission.)

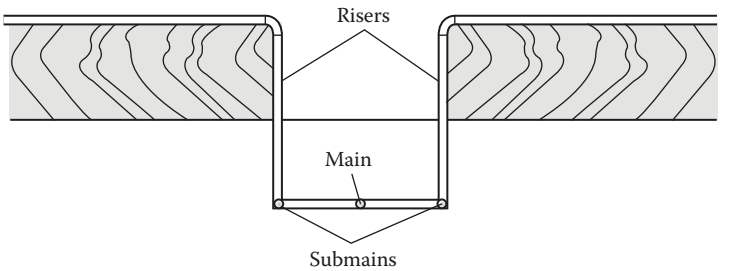

FIGURE 9.14 Main header with submain headers placed underground. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 9.15 Black poly lateral line, emitters, drip lines, and stakes. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

underground close to the main header. It is best to position the main supply line so that the walkway is unobstructed (Figure 9.14).

Pipe sizes must be selected by taking into consideration the flow rates and frictional loss (head) in feet per 100 ft of pipe length of the specific diameter of pipe. The use of a Williams and Hazen formula table will assist in determining the correct pipe size. Otherwise, when laying out a plan of the irrigation system, a qualified person from an irrigation supply store may be asked to do these calculations. The total frictional loss in the system will then determine the size of pump needed to supply the water.

Growers now use emitters of 0.5- to 1-gal/h (2- to 4-L/h) volume instead of spaghetti lines (Figure 9.15). The emitters are inserted directly into the 0.5- or 0.75-in. black polyethylene lateral with a special punch. A drip line is attached to the other side of the emitter and placed at the base of each plant with a special stake that directs the solution down its length to its base as shown in Figure 9.15. The emitters produce a uniform volume of solution and are also available as "pressure-compensating" ones should there be differences in the level of the greenhouse floor.

Pressure-compensating emitters are more expensive than the regular ones, but their output is constant regardless of elevation differences or location along the poly lateral line.

When using these trickle tubes and stakes, check them periodically to determine if any salt buildup or root growth into them that causes plugging occurs. This can be avoided if there are adequate number of irrigation cycles so the plant does not seek moisture and by keeping the stakes pushed into the substrate only about one-quarter of its length. Any root growth plugging trickle lines or stakes can be removed by soaking them in 10% bleach solution for several hours to dissolve the roots. At the end of the season, thoroughly flush the whole system with an acid solution to dissolve any salt deposits.

9.6 ADVANTAGES AND DISADVANTAGE OF SAWDUST CULTURE

The advantages of sawdust culture are as follows:

1. Since sawdust culture, like sand culture, is an open system, there is less chance of spread of diseases such as *Fusarium* and *Verticillium* wilts, especially in tomatoes.
2. There is no problem of plugging of the drainage pipes with roots.
3. There is good lateral movement of nutrient solution throughout the root zone.
4. Plants have good root aeration.
5. A new nutrient solution is added each irrigation cycle.
6. The system is simple and easy to maintain and repair.
7. The high water retention capacity of sawdust reduces any risk of rapid water stress should a pump fail.
8. It is adaptable to fertilizer injectors, and therefore less space for tanks is required.

The disadvantages of sawdust culture are as follows:

1. Sawdust culture is applicable only to areas having a major forest industry; therefore, it is not feasible to use this method in arid desert countries. It is also now becoming unavailable because of its use in lumber by-products such as chip board.
2. Sawdust must be steam or chemically sterilized.
3. Initially, there can be problems of sodium chloride toxicity to plants if the medium is not well leached before planting.
4. Over the cropping season, salt accumulation can occur in the medium to levels toxic to the plants. This toxicity can be reduced by leaching adequately with the nutrient solution during irrigation cycles.
5. Plugging of trickle-feed lines may occur if proper filters are not used or if cleaning of these filters is neglected.
6. If the sawdust used is very coarse, coning of water may occur, causing roots to grow downward rather than laterally.
7. As sawdust is organic in nature, it decomposes with time. Between crops it must be rototilled and a proportion of new sawdust added to make up for that decomposed and that lost on plant roots during the pulling of the plants at the end of each crop.

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10 Rockwool Culture

10.1 INTRODUCTION

Over the past 38 yr, rockwool culture became one of the principal techniques for the growing of vine crops, especially tomatoes, cucumbers, and peppers. Commercial stone wool production started in Denmark in 1937 with the Rockwool Group. In 1949, they started manufacturing rockwool in the Netherlands. Grodan, a subsidiary of the Rockwool Group, was founded in 1969 to research the potential use of stone wool as a substrate in the horticulture industry. In 1979, Grodan began commercial production of rockwool for horticultural use in the Netherlands. Grodan is now established in over 60 countries worldwide.

In a 1986 study by C.J. Graves of the Glasshouse Crops Research Institute in Little Hampton, England (Graves, 1986), the total area (in hectares) of tomato production in Great Britain using rockwool in 1978 was less than 1 ha (2 acres). This increased to 77.5 (197 acres), 126 (320 acres), and 148 ha (376 acres) from 1984, 1985, and 1986, respectively. Similarly, the area of rockwool culture of cucumbers, increased from less than 1 ha (2 acres) to 68 ha (173 acres) over the same period from 1978 to 1986. In 1991, Desmond Day stated that the estimated rockwool production in the United Kingdom was 230 hectares (575 acres) for cucumbers and 160 ha (400 acres) for tomatoes. In the Netherlands, where rockwool manufacturing began, the area of greenhouses using rockwool as a substrate for hydroponic culture is much larger. Rockwool culture is now the most extensively used form of hydroponics in the world, with more than 2,000 ha (5,000 acres) of greenhouse crops being grown using this system in the Netherlands.

Stone wool is made from basalt rock (solidified lava) that is molten in furnaces at a temperature of 1,500°C (2,732°F). The liquid basalt is then spun into threads and hardened in a kiln using hot air at 230°C (446°F) and compressed into wool packets, which are then cut into slabs, blocks, or plugs and wrapped with a plastic cover. One cubic meter of basalt can produce about 90 m^3 of stone wool.

Most of the rapid expansion of the greenhouse industry over the past 23 yr has been with rockwool culture. However, over the past 15 yr there has been concern about the disposal of rockwool, as it does not break down in landfills. Now many growers are turning to an alternative substrate that is natural and environmentally friendly and is sustainable in the form of coco coir (Chapter 11). An example of the now rising use of coconut coir as a substrate is pointed out in the following statistic for the greenhouse industry in Ontario, Canada, where the growing medium for greenhouse vegetable crops is 57% rockwool and 39% coco coir (Statistics Canada, 2008).

Grodan, in an effort to avoid losing market share, offers a recycling program for the spent rockwool. They claim that as a part of their "sustainable business policy" they have set up a recycling service for its growers in specific countries. Grodan recycles the used stone wool into raw material for the production of new stone wool products or other products, such as bricks for construction.

10.2 ROCKWOOL COMPOSITION

As mentioned above, rockwool or stone wool is derived from basaltic rock. It is an inert fibrous material produced from a mixture of basalt, limestone, and coke, melted at 1,500–2,000°C. It is extruded as fine threads and pressed into loosely woven sheets. Surface tension is reduced by the addition of a phenol resin during cooling. While the composition of rockwool varies slightly from one manufacturer to another, it basically consists of silica dioxide (45%), aluminum oxide (15%), calcium oxide (15%), magnesium oxide (10%), iron oxide (10%), and other oxides (5%).

DOI: 10.1201/9781003133254-10

Rockwool is slightly alkaline, but inert and biologically nondegradable. It has good water-holding capacity, with about 95% pore spaces. All fertilizers must be added to the irrigation water for plant growth. Rockwool has about an 80% water-holding capacity. The *p*H of rockwool is between 7 and 8.5. Since it has no buffering capacity, the *p*H can easily be reduced to optimal levels of 6.0–6.5 for tomatoes and cucumbers by the use of slightly acid nutrient solution.

Rockwool culture in the past was generally an open, non-recycling hydroponic system, with nutrients fed to the base of each plant with an emitter and drip line. Approximately 20–30% excess solution was supplied during each watering to leach minerals from the rockwool slabs to prevent salt buildup. Today, with the emphasis on the environment and the reduction of the environmental "footprint" of any operation, recirculation of nutrient solution from the leachate of the rockwool system has become imperative. Now, the rockwool is supported by channels that collect the leachate and recirculate it back to the central injection area where it is treated for disease control and its *p*H and electrical conductivity (EC) adjusted by injectors. This is discussed in more detail later in Chapter 12.

Information on growing vegetables using rockwool culture is presented in a number of articles and manuals (Bijl, 1990; Hochmuth, 1992; Marlow, 1993; Smith, 1986).

10.3 ROCKWOOL CUBES AND BLOCKS

Tomatoes and peppers are seeded in rockwool cubes 1.5 in. x 1.5 in. x 1.5 in. (3.75 cm x 3.75 cm x 3.75 cm) (Figure 10.1) or in granular rockwool in Styrofoam trays of 240 cells. Cucumbers may be seeded in rockwool cubes or directly into blocks (Figures 10.2 and 10.3). After sowing the seed in cubes or blocks, the seed may be covered with coarse vermiculite to maintain moisture during germination and to assist the plant in removing its seed coat, but this is not a standard practice as it is time consuming. It is very important to soak the rockwool well before sowing seeds. This is usually done with a dilute nutrient solution of EC 0.5 mS (milli Siemens) to assist in adjusting the *p*H. It is

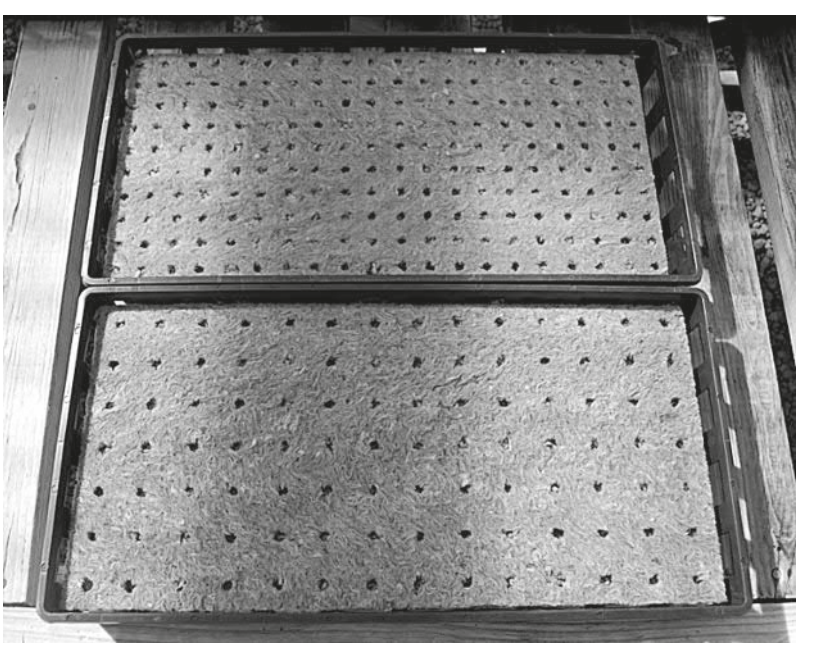

FIGURE 10.1 Rockwool cubes. Background: 1 in. x 1 in. x 1.5 in. deep (200 cubes/flat). Foreground: 1.5 in. x 1.5 in. x 1.5 in. deep (98 cubes/flat).

FIGURE 10.2 Cucumbers seeded in rockwool cubes.

better practice to sow the seeds in rockwool cubes and transplant them to rockwool blocks than to seed directly in the blocks as this allows more efficient use in the propagation area.

The trays are watered with raw water until germination takes place and then with a dilute nutrient solution thereafter until first true leaves begin to unfold. Tomato seedlings are usually transplanted to rockwool blocks within 2–3 wk, depending on their growth rate. Cucumbers are transplanted to the blocks earlier, usually between 6 and 10 d. The seedlings with their cubes are transplanted into rockwool blocks having large holes (Figures 10.4 through 10.6). Presoak the blocks with nutrient solution of EC 2.5 mS and *p*H of 6.0 at 23°C (73°F).

Rockwool blocks are available in a number of sizes, 7.5 cm x 7.5 cm x 6.5 cm (3 in. x 3 in. x 2.5 in.); 7.5 cm x 7.5 cm x 10 cm (3 in. x 3 in. x 4 in.); 10 cm x 10 cm x 6.5 cm (4 in. x 4 in. x 2.5 in.); and 10 cm x 10 cm x 8 cm (4 in. x 4 in. x 3 in.) (length x width x height). The growing blocks are manufactured in strips, each block individually surrounded by a plastic wrapping. The choice of the growing block is determined by the plant being grown and the stage at which the grower wishes to transplant to the final rockwool slabs. Many growers transplant two plants per double rockwool block, which is 6 in. x 3 in. x 2.5 in. high (15 cm x 7.5 cm x 6.5 cm), or one per large block, which is allowed to form two stems. Transplant six plants per slab or in high light areas, four blocks, each with one seedling that is permitted to branch to give equivalent to eight plants per slab.

The longer the grower wishes to hold the plants in a seedling area, the larger blocks he should use (Figures 10.3 through 10.6). While the smaller blocks are good for tomatoes and peppers, the larger ones are more suitable for cucumbers, which grow rapidly. By placing the blocks on wire-mesh benches, roots that grow out of the bottom of the blocks are air pruned. This keeps the bulk of the roots inside the block and lessens transplant shock.

10.4 ROCKWOOL SLABS

Slabs are enclosed in a white polyethylene sheet cover. They are available in a number of sizes, 90 cm x 30 cm x 5 cm (35.5 in. x 12 in. x 2 in.); 90 cm x 15 cm x 7.5 cm (35.5 in. x 6 in. x 3 in.);

FIGURE 10.3 Cucumbers seeded in rockwool blocks.

FIGURE 10.4 Tomato plants transplanted into rockwool blocks after 3 wk. Note: If the plants are not grafted they can be laid on their sides in the blocks.

90 cm x 20 cm x 7.5 cm (35.5 in. x 8 in. x 3 in.); 90 cm x 30 cm x 7.5 cm (35.5 in. x 12 in. x 3 in.); and 90 cm x 45 cm x 7.5 cm (35.5 in. x 18 in. x 3 in.) (length x width x thickness).

Slabs that are 15–20 cm (6–8 in.) wide are generally recommended for tomatoes and peppers, those that are 20–30 cm (8–12 in.) wide for cucumbers, and those that are 30 cm (12 in.) wide for melons. Wider slabs for tomatoes can lead to excessive vegetative growth if only two or three plants are grown in each. The trend now is to use the wide slabs and grow four to six plants in them. Slabs

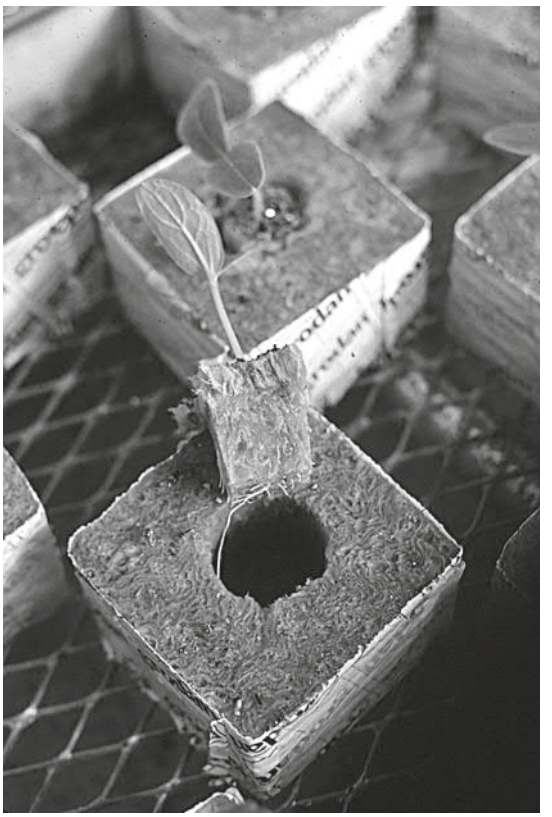

FIGURE 10.5 Cucumber seedling in rockwool cube is transplanted to rockwool block with a large hole.

FIGURE 10.6 Author transplanting cucumber seedlings. (From Environmental Farms, Dundee, FL. With permission.)

are also available in several densities. Higher density slabs will maintain their structure when used for several crops over a period of 2–3 yr and especially when steam sterilized between crops.

Owing to their cost, it is more cost effective to use the same slabs for 2–3 yr (crops) by steam sterilizing between crops or changing the crop. For example, if a greenhouse operation grows tomatoes, cucumbers, and peppers, the tomatoes can be grown in the new slabs, which are subsequently used for cucumbers and peppers. There will be some structural breakdown resulting in a 10–15% loss, but this may be reduced by using the higher density slabs.

To sterilize the slabs, they must be stacked on pallets after removing the plastic wrapping. They should be stacked with each layer in opposite directions, with some air spaces between so that the steam will penetrate the entire pile. They are covered with canvas and steam piped into the pile under the covering. The center slabs must reach a temperature of 60–80°C (140–180°F) throughout for 30 min to be assured of complete sterilization. The slabs are rewrapped after sterilization.

Grodan now makes five kinds of slabs in an attempt to better suit specific crop needs. The Grodan Classic M/Y is for use for several cropping seasons. Its water content (WC) can easily be modified for seasonal differences in crop demand for water to facilitate crop steering (vegetative vs. generative phases) (Chapter 16). Grodan Vital is a single-season slab and is suitable for tomatoes, peppers, cucumbers, and eggplants. They claim that the WC can fluctuate with no problems, within a safe range between 55% and 78% (day level). The slab can be re-saturated quickly if it contains insufficient water. The others, Grotop Expert, Grotop Master, and Grotop Master Dry, all have different WC content percentages to assist in steering plants toward being more vegetative or generative.

10.5 ROCKWOOL LAYOUT

Rockwool culture was first designed as an open, nonrecycling hydroponic system. More recently, the use of recycling systems with rockwool culture is emphasized as the awareness of the environment and conservation of water is becoming more important. Such recycling systems are discussed later. Nutrients are fed to the base of each plant with a drip irrigation line and emitter. Approximately 15–20% excess solution is supplied during each watering to allow leaching of minerals from the rockwool slab.

A typical layout for an open-system rockwool culture is shown in Figure 10.7. Before placing the growing slabs out, the greenhouse floor area should be disinfected and then the soil surface (floor) should be leveled. Beds consist of two rockwool slabs set 60–75 cm (2–2.5 ft) apart for cucumbers. With tomatoes and peppers the slabs may be closer, generally 40–45 cm (16–18 in.), depending on the specific plant row spacing required. Soil or sand makes the best floor as it can be easily formed to obtain good drainage. A slight slope toward the center between the two slabs will provide adequate drainage away from the slabs. The entire greenhouse floor area is covered with a white-on-black polyethylene of 6 mil thickness to provide light reflection and good hygiene (Figure 9.11). If the drainage conditions in the greenhouse are poor, it is necessary to lay a drainage pipe in the middle of the bed. The drainage pipe should be covered with pea gravel and/or coarser sand, and the white ground sheet placed on top of it. If this method is used, the ground sheet should have small holes punched in it to allow percolation of the excess nutrient solution to the drainpipe. Alternatively, the unpunched polyethylene sheet will act as a drainage channel to conduct excess solution to a drainpipe at the far end of the greenhouse. However, problems with algae may develop if stagnant water remains in the channel, which also promotes an environment for fungus gnats. To avoid algae and fungus gnats, it would be better to use a nursery weed mat on top of the underlying substrate. The weed mat would permit water to pass through it to the substrate underneath.

In more northerly latitudes where the ground temperature is cold, it is advantageous to place the slabs on top of 1-in. (2.5-cm) to 4-in. (10-cm)-thick Styrofoam sheets. Today, almost all growers use collection channels in which the slabs are set to collect the drain water and return it to a central treatment area. This will be discussed in detail later.

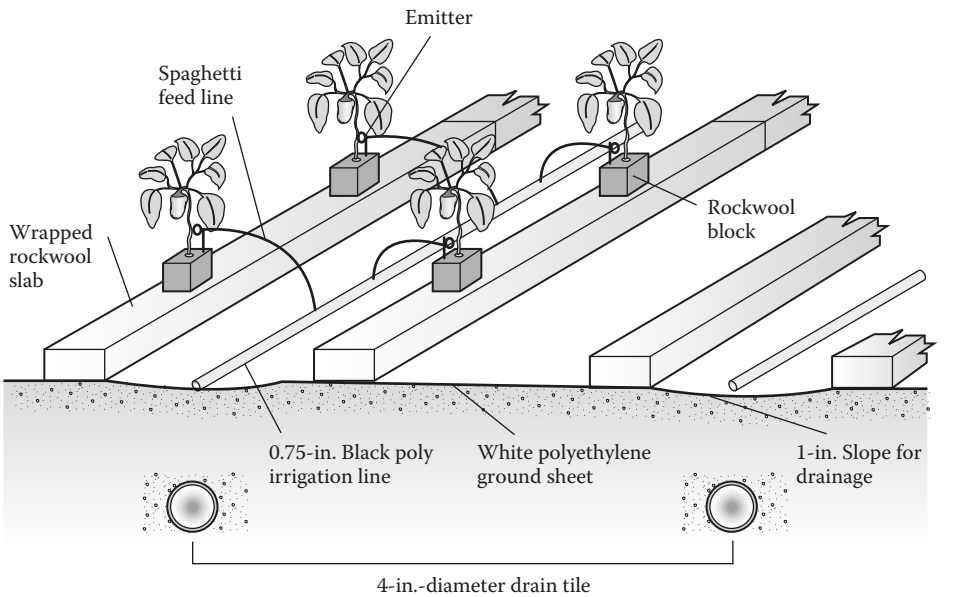

FIGURE 10.7 Sketch of an open system of rockwool culture. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

Most growers now use the high-density rockwool slabs placed in a single row and V-cordon train the plants. Five to six plants are set on each slab. This reduces the cost of slabs and still provides sufficient growing space for the plant roots.

10.6 IRRIGATION SYSTEM

A drip irrigation system with a fertilizer injector as shown in Figure 10.8 provides nutrients to each plant individually. A drip emitter of 0.5 gal/h (2 L/h) feeds each plant via a drip trickle line. A PVC main line must be of sufficient diameter (minimum of 3 in.) to supply the area of the greenhouse section to be irrigated at a given time. From the main, submails or headers distribute solution to subsections. Risers (usually 1-in. diameter) join the 0.75-in. black poly lateral of each row to the header. These diameters may be increased to 1.5 and 1 in., respectively, with long laterals up to 200–300 ft. If the emitters are punched directly into the lateral line at the plant spacing rather than putting them at the end of the drip line, less plugging will occur, as they do not dry out between watering cycles. Spitter-type emitters should not be used, as they will moisten the base of the plants and promote diseases. Special small ribbed stakes are attached to the end of the emitter trickle line and support the drip line on the rockwool blocks or slabs (Figure 10.9).

The rockwool slabs must be soaked with nutrient solution of EC 2.5–3.0 mS and *p*H of 6.0 before transplanting (Figure 10.10). The slabs will be soaked with nutrient solution for 24–48 h. This will adjust the *p*H and uniformly moisten the slabs. To do this, place the slabs in their final position, with three drip lines entering a small slit on top of each slab at equal spacing. Operate the nutrient system until the slabs swell as they fill with solution. Do not cut drainage holes in the slabs until they have been soaked. Check that all of the slabs are soaked. Usually, a few slabs are found that have holes in their wrappers, and they do not soak properly. If this happens, the growth of the plants on such a dry slab will be greatly restricted.

Following the first irrigation after transplanting, the slabs should again be checked for dry spots between the drip lines, as the slabs must be fully saturated to ensure sufficient solution reserves for

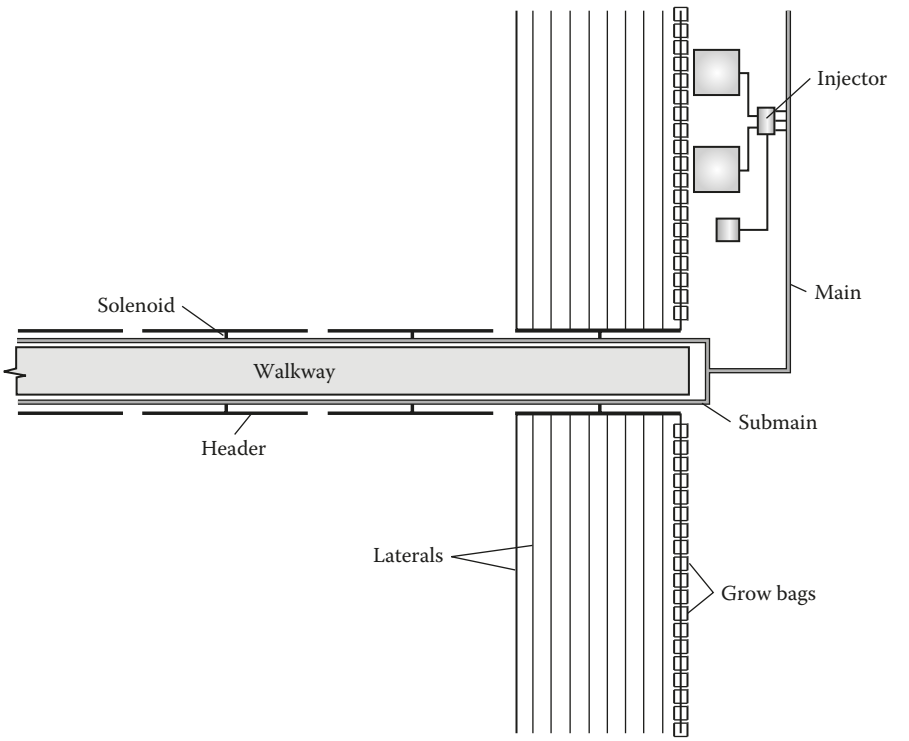

FIGURE 10.8 Rockwool irrigation system plan. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 10.9 Drip line with ribbed stake placed at the edge of the block

the plant during the initial posttransplant period. Drainage holes must be cut on the slab sides at the bottom edge (Figure 10.11). They should be in the shape of an inverted "T" or an angled straight cut approximately 4–5 cm (2 in.) in height. Two or three holes should be made in each slab on the inside face. Make the cuts between plant locations, not directly under them, or the solution will run immediately out of the holes and not be forced to flow laterally.

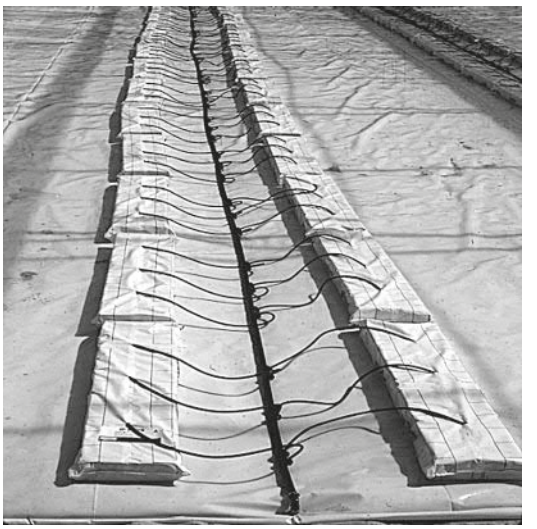

FIGURE 10.10 Soaking of slabs before transplanting.

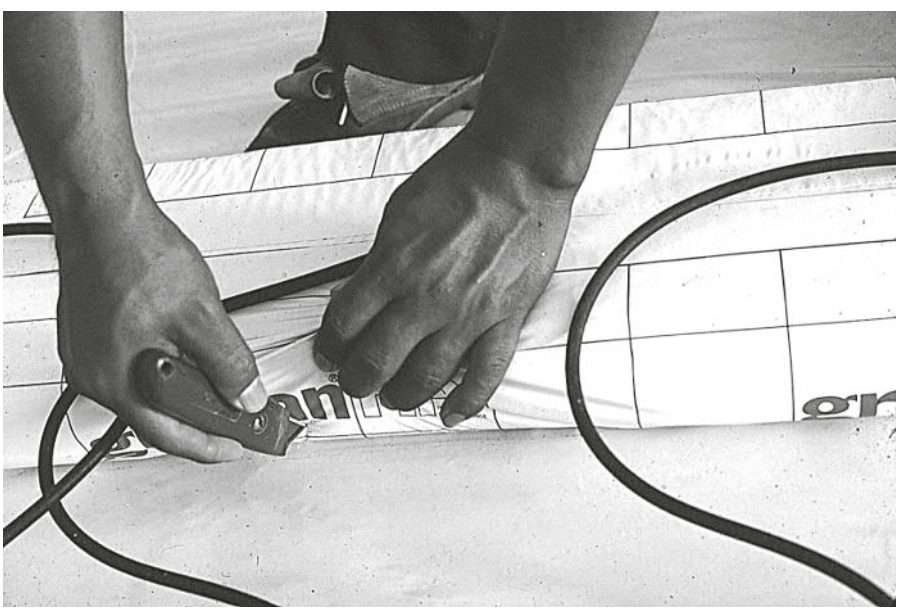

FIGURE 10.11 Cutting drainage slits on the inside bottom face of the slabs.

Cut holes in the polyethylene wrap at the top of the slabs in the locations where the transplants are to be set. While transplanting, simply set the rockwool blocks growing the seedlings on top of the slabs through the holes cut in the plastic sleeve. Place a drip line at the edge of the block with a stake. Use the ribbed stakes to prevent any spray onto the crown of the plant to reduce disease infection. Push the stakes about one-third of their length into the block, because if they are pushed too deep into the block or slabs, plant roots may grow up into them. Little transplant shock is encountered by the plants using this rockwool system of blocks. The roots will grow from the blocks into the slabs within several days.

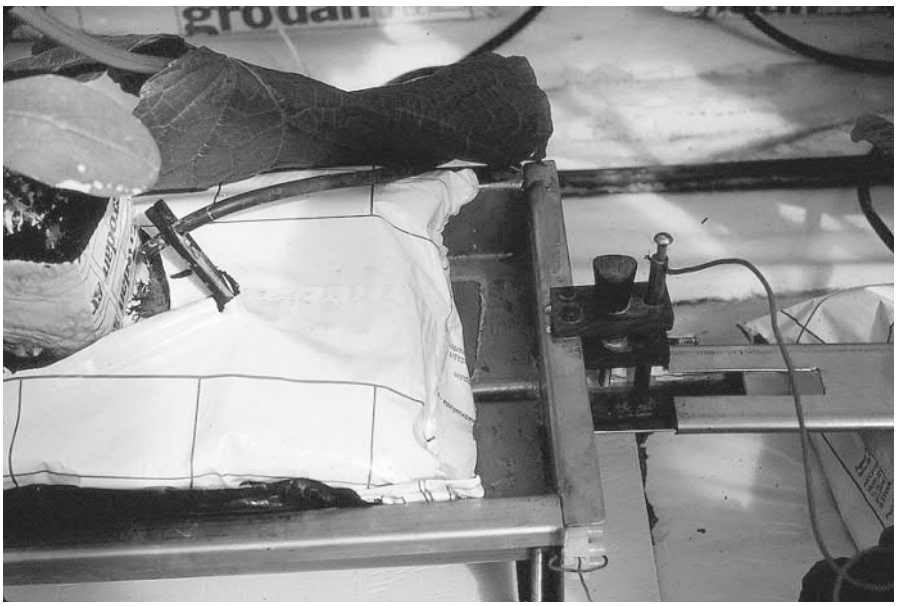

FIGURE 10.12 Start tray monitors the amount of solution present in the slab. (From Environmental Farms, Dundee, FL. With permission.)

Before transplanting, all of the support strings should be strung to the overhead wires. When transplanting, attach the string to the plant, with a plant clip located under the first set of true leaves. Do not pull the string too tight, so that it can easily be wound around the plant as it grows.

More frequent irrigation is necessary immediately after transplanting until the plants become established. Later, a frequency of five to eight times per day should be adequate, with rates varying according to plant stage of growth and environmental conditions.

Irrigation cycles in large greenhouse operations are controlled by a computerized system that monitors ambient weather conditions and moisture levels in the slabs and regulates irrigation cycles accordingly. In this case, a slab, representative of all slabs growing the crop, is selected and placed in a "start tray" (Figure 10.12). The start tray monitors the amount of solution present in a slab growing healthy plants. The bottom of the wrapper is removed from the slab placed in the start tray so that excess solution drains easily. A V-shaped groove in the bottom of the stainless steel tray conducts the solution to one end where an electrode is positioned. As long as there is adequate solution present, the solution is in contact with the electrode and the circuit complete. The signal then prevents an irrigation cycle from being initiated. As soon as the circuit is broken, as the solution falls with the drying of the slab due to uptake by the plants, an irrigation cycle begins and will continue for the preset time interval set in the irrigation controller or computer. Smith (1987) stated that watering should be done before the slabs have lost more than 5–10% of their water-holding capacity. The moisture level in the slabs may be raised or lowered by raising or lowering the probe in the start tray. That is, if a higher moisture level is to be maintained between irrigation cycles, the probe may be raised, and as a result, more frequent irrigation cycles will occur.

The duration of an irrigation cycle should be long enough to get a 20–25% runoff from the slabs. The drainage from the slabs may be determined by setting up a special collection tray under one of the slabs having healthy plants (Figure 10.13). A pipe outlet at the lower end of the collection tray directs the waste solution to a container below, buried in the floor. A second container collects the solution from one emitter. This gives the amount of water which actually came out of each emitter, assuming they are all equal. If pressure-compensating emitters are used, the flow through

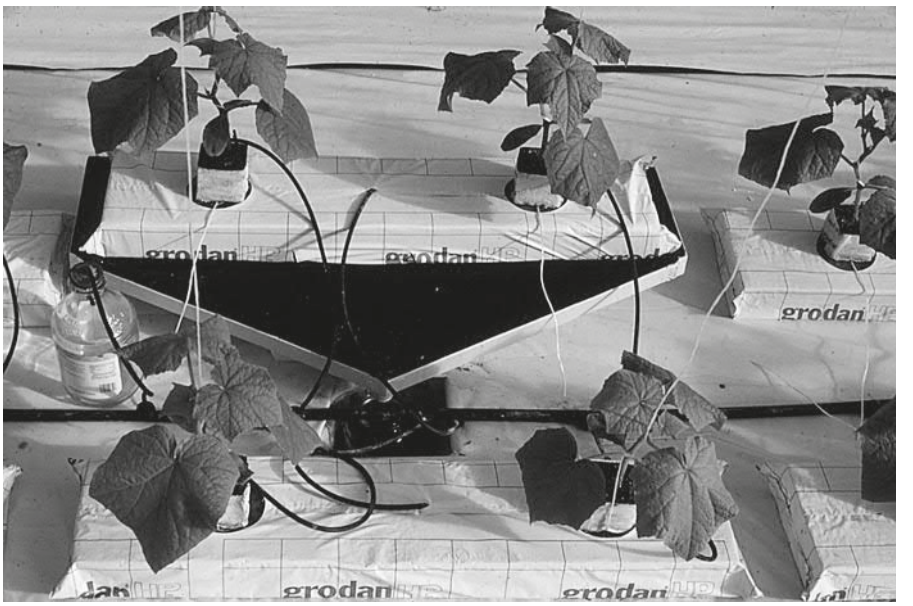

FIGURE 10.13 Collection tray to monitor the amount of solution runoff from the slab. (From Environmental Farms, Dundee, FL. With permission.)

each should be the same. To get the volume of solution that entered the slab, multiply the volume collected from the one emitter by the number of emitters in each slab. Divide the waste volume from the collection tray by this inlet volume from the emitters. It is easiest to use milliliters as a volume measurement. A graduated cylinder will suffice to measure the liquids.

Systems of root zone monitoring that are more advanced than these start and collection trays are now used. Good root growth, which avoids diseases and waste of water and fertilizers and steers crops to optimize yields and quality, can be achieved by tightly controlling root zone conditions. To do this, irrigation quantity, frequency, EC, and *p*H must be controlled and adjusted to achieve ideal root conditions. The media must be allowed to dry down somewhat overnight and rapidly wet up in the morning. The media leachate must be sufficient to avoid salt buildup (excessive EC) while at the same time keeping it satisfactorily moistened.

An automatic data logging system, such as that of Autogrow (www.autogrow.com), uses a moisture probe that remains embedded in the media. Their "Minder" system measures the irrigation quantity (from one dripper) together with the EC and *p*H, the moisture level, media temperature, and runoff quantity, including its EC and *p*H. It calculates the runoff ratio and displays it as a graph together with ECs, *p*Hs, media moisture, and temperature. In addition to the root zone parameters, a solar sensor measures the sunlight received. This information is sent to a computer that controls the irrigation cycles and duration according to preset levels. This type of feedback control optimizes irrigation cycles according to existing conditions within the root zone and available light (Broad, 2008). Other computer controllers that perform similar functions include Argus Controls (www.arguscontrols.com) and Priva (www.priva.nl).

Salt levels in the rockwool slabs should be monitored at least every other day. Greenhouses having computers may have a number of EC and *p*H sensors in slabs at several locations in the house, giving continuous monitoring. Otherwise, a sample must be taken from the slab with a small syringe and tested for its *p*H and EC (Figure 10.14). Values should be close to those of the nutrient solution provided to the plants. If significantly high levels of conductivity or nonoptimal *p*H levels are detected, the slabs must be irrigated more often until their solution concentration approaches that

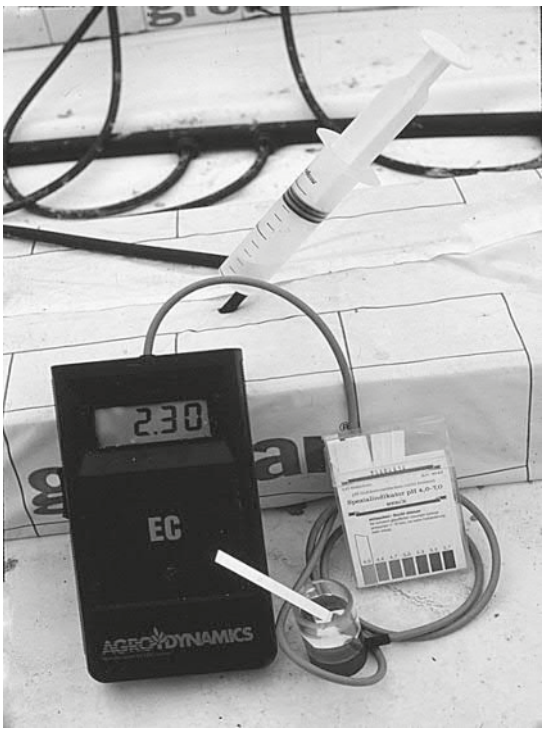

FIGURE 10.14 Testing the slab solution EC and pH with an EC meter and pH paper.

of the input solution. "Clear" raw water should not be used as it often contains sodium, calcium, and magnesium. These ions will accumulate in the slabs, and other nutrients such as potassium, nitrates, and phosphates will be depleted, causing an imbalance in the slab nutrition.

10.7 CUCUMBERS IN ROCKWOOL

Cucumbers were grown at Environmental Farms, Dundee, Florida. An existing greenhouse of 1.5 acres (0.6 ha) that had been previously a citrus nursery was converted to rockwool culture of cucumbers. The floor was filled with 6 in. (15 cm) of sand after drainage tiles were installed. The floor was contoured for the rockwool slabs and a white polyethylene liner placed on it. A drip irrigation system was installed and the cucumbers seeded in rockwool cubes and transplanted to blocks (Figures 10.2, 10.5, and 10.6). Fourteen days from seeding they were transplanted to the slabs (Figure 10.15). They became established in the slabs within 2–3 d and grew close to 6 in./d (15 cm/d). Eighteen days from transplanting (32 d from seed), they reached 5 ft (1.5 m) in height (Figure 10.16).

European cucumbers are trained using the "renewal umbrella" system. All of the small stem fruit have to be removed up to at least the seventh or eighth leaf. All of the side shoots are removed except the top two nearest the support wire that are permitted to grow over the wire and hang down as the top of the main stem of the plant is cut just above the wire. For more details on the plant training, refer to Chapter 16. Harvesting began at 40 d from seeding (Figure 10.17). The fruit was harvested in the late morning after the plants had dried out. Plastic tote bins were used to harvest the fruit and were transported to the packing area by a tractor and trailer (Figure 10.18). The cucumbers were shrink-wrapped with an L-bar sealer and oven (Figure 10.19). Larger operations, such as Houweling's Group in Camarillo, California (Chapter 12) use a large oven shrink wrapper

FIGURE 10.15 Fourteen days after seeding, cucumbers have been transplanted to the slabs. (From Environmental Farms, Dundee, FL. With permission.)

FIGURE 10.16 Cucumbers 31 d after seeding (18 d after transplanting). (From Environmental Farms, Dundee, FL. With permission.)

(Figure 10.20). The cucumbers are packed 12 fruits to a case, palletized, and placed in cold storage at 50–55°F (10–13°C) (Figure 10.21). Environmental Farms had three grades, regular, large, and jumbo, which were determined by the length of the fruit. Most of the product was shipped to the northeastern United States and Canada.

FIGURE 10.17 Beginning of harvest, 40 d after seeding. (From Environmental Farms, Dundee, FL. With permission.)

FIGURE 10.18 Fruit is harvested in plastic tote bins. (From Environmental Farms, Dundee, FL. With permission.)

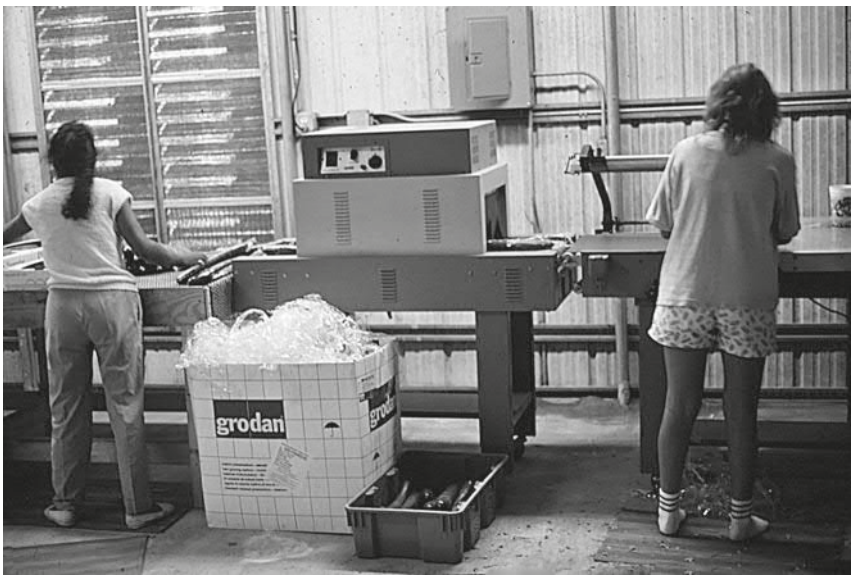

FIGURE 10.19 Cucumbers may be shrink wrapped with an L-bar sealer. (From Environmental Farms, Dundee, FL. With permission.)

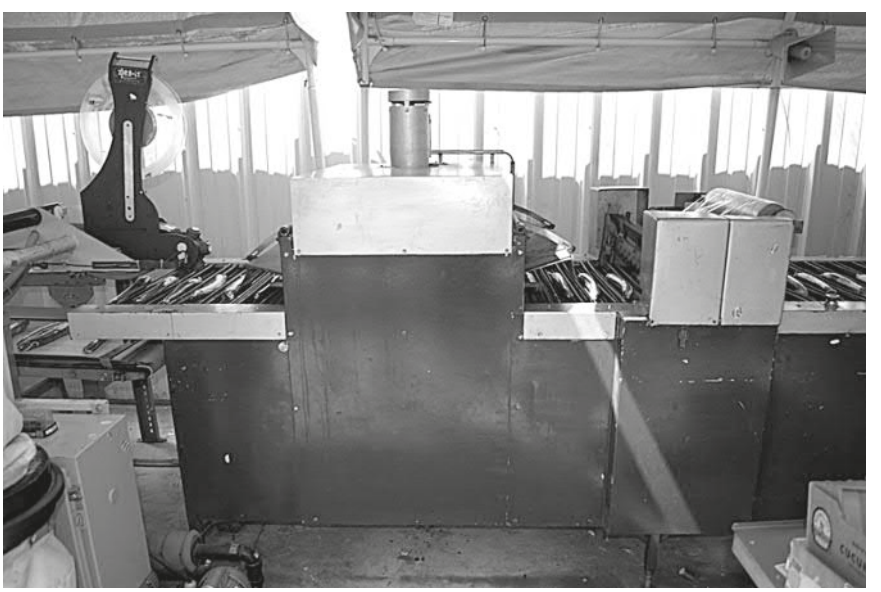

FIGURE 10.20 Large commercial shrink wrapping machine. (From Houweling's Group, Camarillo, CA. With permission.)

As with any agricultural crop, pest and disease problems arose. The most troublesome pests included aphids, whiteflies, and thrips. With the humid conditions of Florida, gummy stem blight and mildew diseases were present. Powdery mildew was overcome by use of a resistant variety, Marillo. Gummy stem blight was prevented by painting a fungicide on the base of the plant stem. Viruses were the most challenging. Aphids and whiteflies were the vectors. Control of the viruses

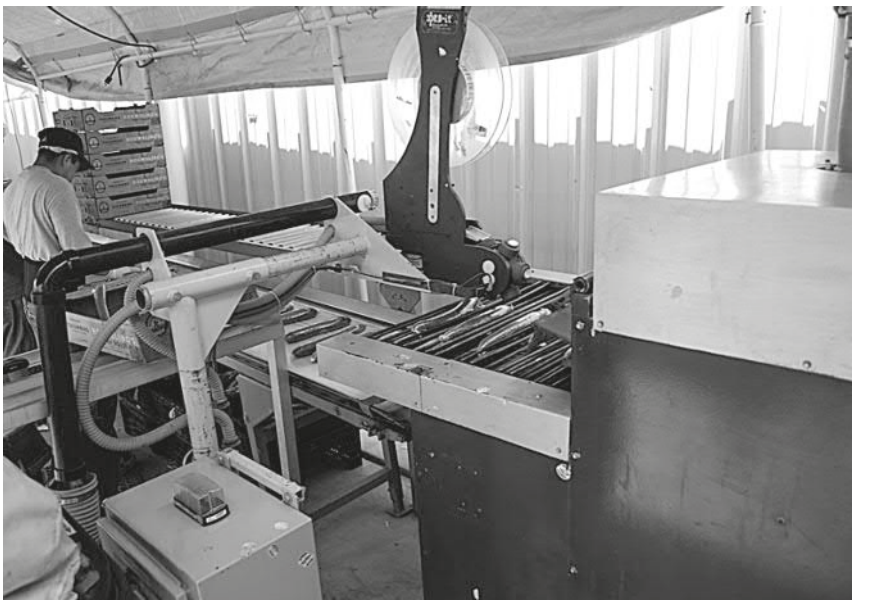

FIGURE 10.21 After labeling, the cucumbers are packed 12 fruits to a case. (From Houweling's Group, Camarillo, CA. With permission.)

depended largely on control of the insect vectors. The spread of viruses during pruning, training, and harvesting by the workers was prevented by dipping tools in a milk bath carried by the workers. This dip was necessary between touching each plant.

A fogger was used to apply pesticides (Figure 10.22). It dispersed a suspension of fog through the crop canopy as it was pushed on a cart down every row (Figure 10.23).

Modified renewal umbrella training with only one leader growing over the wire was adopted as the cucumbers in Florida are extremely vigorous with the amount of sunlight present. With the existence of high insect populations and disease inoculums because of the semitropical conditions of Florida, most cucumber growers change their crops every 3–4 mo as diseases and insects eventually infect the crop severely enough to substantially reduce yields.

Houweling's Group, Delta, British Columbia grows two crops of European cucumbers annually. The first crop is seeded on December 1 and transplanted in late December, with first harvest by early February. Production continues until June. A second crop is seeded in June in a separate seedling range. Three-week-old plants are transplanted, and production commences within 3 wk and continues until mid-November.

Cucumbers are planted at a density of 1.2–1.4 plants per square meter (10.76 ft^2), which is 5,000 plants per acre (12,500 plants per hectare). While the industry average annual production was 110 cucumbers per square meter in the late 1990s, this operation produced over 140 cucumbers per square meter. This is equivalent to 10–13 fruits per square foot or 73–93 fruits per plant. Growers today produce an average of 120 fruits per year per plant. This is partly due to improved varieties that yield higher because of disease resistance, more vigor, and to improved growing techniques.

10.8 TOMATOES IN ROCKWOOL

Seedlings are started in flats of 1-in. rockwool cubes and after 12–14 d transplanted to 3-in. (7.5-cm) or 4-in. (10-cm) rockwool blocks. The larger blocks are used so that the plants will not dry out as quickly when placed on top of the rockwool slabs before positioning them inside the slab wrapper.

FIGURE 10.22 A fogger can apply pesticides effectively to high-density crops. (From Environmental Farms, Dundee, FL. With permission.)

FIGURE 10.23 It is important to use protective clothing when applying pesticides. (From Environmental Farms, Dundee, FL. With permission.)

To overcome *Fusarium* crown and root rot disease, a resistant rootstock variety is used in the absence of a commercially resistant variety. For tomato-on-vine (TOV) cultivars, such as "Tricia" and "Success," a "Maxifort" rootstock is used. This same rootstock is commonly used for other TOV varieties and beefsteak varieties such as "Caramba." "Beaufort" rootstock is used with cherry tomato varieties such as "Favorita." Both varieties (scion and rootstock) are germinated at 79°F

(26°C). The scion is the upper part of the plant, which is the desired variety such as Tricia, Success, Caramba, Favorita, and so on. After germination, the two seedlings are grown in separate sections of the greenhouse under different temperature regimes. The rootstock is grown at 64°F (18°C), and the scion variety at 72°F (22°C). To obtain a thicker stemmed rootstock, the rootstock variety is sown 2 d earlier than the scion variety. The rootstock variety is grown for 14 d and the scions for 12 d before grafting. This is termed *green grafting*. The procedure is discussed in Chapter 16. Most growers now contract to a specialized grower of transplants who grafts the seedlings. Bevo Agro Inc., Langley, British Columbia, and Houweling's Group, Delta, British Columbia are two such operations.

A typically cropping schedule in British Columbia is to purchase 6-wk-old grafted seedlings from a nursery grower and transplant in the first week of January. There are two plants in each rockwool block (Figure 10.24). When transplanting, the blocks with the seedlings are placed on top of the slabs, but not in them until the first flower truss opens. The plants are allowed to bifurcate at the first truss. This is about January 17 in British Columbia. This bifurcation will increase plant density from 1.65 to 3.3 stems per square meter, which is equivalent to 6.5–3.26 ft^2 per plant. In high sunlight areas, such as southern California and Arizona, tomatoes are allowed to bifurcate early in their growth (Figure 10.25). In northerly areas, such as British Columbia, bifurcation is practiced later so that there is sufficient light with increasing day length in the subsequent months as the plants grow with two stems. This procedure increases production. Beefsteak tomato annual yields average between 50 and 75 kg/m^2 (10–15 lb/ft^2 or 33–50 lb per plant).

FIGURE 10.24 Two grafted tomato seedlings per rockwool block. (From Houweling's Group, Camarillo CA. With permission.)

FIGURE 10.25 Bifurcation of tomato plants at an early stage in high light areas. (From Eurofresh Farms, Wilcox, AZ. With permission.)

This unique training system was adopted to save on rockwool blocks and slabs. Two blocks, each with two plants, instead of the conventional three blocks with one plant each, were set onto each slab. Slabs and plants are spaced to get centers of 75 cm (30 in.) within rows by 45–50 cm (18–20 in.) between rows. That is, two rows of slabs were used for two rows of plants. Now, they use only one row of slabs and double the number of plants and blocks on the slabs. The plants are V-cordon trained upward to the support wires. This gives the same area per plant, but utilizes half the slabs. This is equivalent to 0.6 m^2 (6 ft^2) per plant. This is reduced to the normal final spacing of tomatoes of 0.3 m^2 (3 ft^2) per plant by mid-April when light has improved. Plant density is increased by letting each plant form two shoots. By the end of February, one-sixth of the plants are allowed to form a second shoot by letting one healthy sucker grow. This procedure is continued over a period of 2 mo, so that by the end of April every plant has two stems and therefore the plant density is doubled.

Gipaanda Greenhouses in 1993 did trials on TOV varieties at spacing of 1.8 going up to 3.6 stems per square meter (6–3 ft^2 per plant). Resulting yields reached 63 kg/m^2 (13 lb/ft^2 or 38.6 lb per plant). Other specialty tomatoes (cherry, Japanese berry, and grape) spaced at 3–6 stems per square meter (3.6–1.8 ft^2 per plant) yielded between 25 and 30 kg/m^2 (5.5–6 lb/ft^2).

Plants are supported by polyethylene twine about 30 ft (9 m) long for each plant. The string is wound around double hooks, which hang from the overhead wire support (Figure 10.26). The plant vines reach 25–30 ft (7.6–9 m) by the end of the season. Plants are lowered by untying the string from the hooks (tomahooks). Plant stems are looped around the ends of each bed by use of a 3-in.-diameter plastic drain-tile pipe or other wire supports to prevent breakage (Figure 10.27). The stems are laid along the top of the slabs. Wire hoops about 0.19 in. diameter placed across the slabs support the plant stems (Figure 10.28). This method now has been updated to using the small pipe support frame of the raised trays to support the stems (Figure 10.29). Raised trays, now used for rockwool and coco coir cultures, are discussed in detail in Chapter 11.

Keeping the bare stems supported above the floor and slabs permits good ventilation and maintains the stems dry so that fungal infection is avoided. It also keeps the scions above the slabs so that they will not root into the blocks.

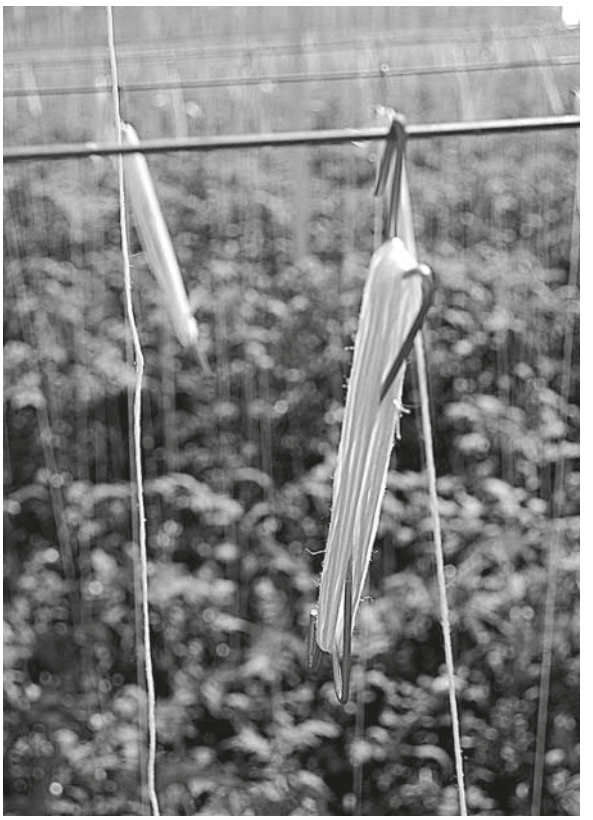

FIGURE 10.26 Tomahook with string to support plants. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 10.27 Plants are bent around the end of the row using a 3-in. pipe. (From Gipaanda Greenhouses Ltd., Delta, B.C., Canada. With permission.)

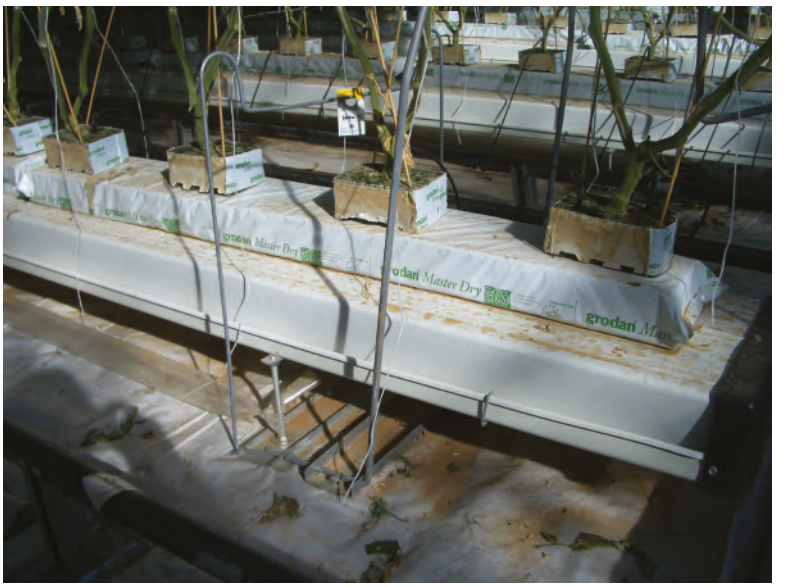

FIGURE 10.28 Wire hoops support the plant stems above the floor. Note: The slabs are set on top of FormFlex trays. The collection lip on the sides of the trays recycles the solution. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 10.29 New stem support used with raised beds. (From Houweling's Group, Camarillo, CA. With permission.)

The management of irrigation is important in rockwool slab oxygenation (Ryall 1993). The last irrigation should be done 2.5–3 h before sunset to reduce the solution retention in the rockwool slabs to 65% of their capacity. This drying of the slabs to create a water deficit overnight allows better oxygenation of the roots. Active root growth is encouraged by the overnight water deficit in the slabs. The first irrigation occurs about 2 h after sunrise. Subsequent irrigations are initiated by the computer according to light availability. On a bright sunny day it may irrigate up to 20 times. Overall, the slabs are irrigated to give a 40% leachate during irrigation cycles. During heavy demand for water during midday, the over drain may be increased to 60%.

This management of irrigation has been further substantiated by Jeff Broad (2008) as irrigation techniques are used to steer crops (to correctly balance vegetative and generative plant phases). He pointed out that watering stop time is used to steer the plants. Stopping earlier will cause greater dry down of the rockwool slabs and steer the plants toward generative. However, he points out that if the slabs are allowed to dry too much, it will be difficult to wet them up the next day. The watering start time he recommends is close to sunrise and not later than 2 h after sunrise. Too close to sunrise or before sunrise may cause fruit splitting in tomatoes. Too far after sunrise may make it difficult to wet up the slabs as the crop takes water from the media before irrigation commences.

10.9 LARGE GREENHOUSE OPERATIONS IN NORTH AMERICA

As examples of large greenhouse operations and their growing procedures, Eurofresh Farms in Wilcox, AZ and Houweling's Group, Camarillo, California are described. Eurofresh Farms has five 53-acre (21-ha) complexes for a total of 265 acres (106 ha) in Wilcox and another 53-acre (21-ha) facility in Snowflake, Arizona. Eurofresh Farms fell into bankruptcy and was sold to NatureSweet in 2013. NatureSweet sold the Snowflake, Arizona facility in 2016 to Copperstate Farms who converted it to a cannabis growing facility. All of the greenhouses are glass Venlo Dutch structures having 6-m (19.7-ft) gutters (sidewalls). Eurofresh Farms grew mainly TOV tomatoes, with one complex (site) of cucumbers. They also grew cherry and other specialty tomatoes. The greenhouses have cooling pads, with fans drawing air from the interior passageway between ranges. The rows of plants are 114 m (374 ft) on either side of the central passageway within the greenhouse.

In 2007, Eurofresh Farms were using a De Ruiter (Monsanto purchased De Ruiter in 2008) TOV variety, "Brilliant," grafted to a "Maxifort" rootstock. Other TOV varieties they used included "Campari," "Lorenzo," and "Balzano," grafted to "Maxifort." They also grew "Conchita" (cherry) and "Savantis" (roma/plum) varieties. For more detailed information on tomato varieties, refer to Chapter 16.

A recirculating rockwool system is designed to take the leachate back to a storage tank where it is sterilized with ultraviolet (UV) lights, the EC and *p*H monitored, and stock solutions are injected according to computer settings (Figure 10.30). The standard recycling trays by Formflex are raised about 10 in. (25 cm) above ground level by a steel frame that allows the bed to be adjusted to get an even slope to the return end without low spots along the channel (Figure 10.28). The rockwool slabs lay on top of Styrofoam insulation to maintain root temperatures. There are wire plant supports placed over the gutters. A single row of channel is set for each plant row. Each rockwool slab contains four bifurcated tomato plants that are trained in a V-cordon fashion to the above support cables via plastic twine. This enables each row in effect to have an equivalent number of plants as the normal two rows. This method saves on the number of rockwool blocks, slabs, and raised gutters compared to two rows of single-stemmed tomato plants.

FormFlex, a company of The Netherlands, has distribution centers in the United States and Canada. Their website is www.formflex.nl for The Netherlands and www.formflex.ca for Canada. FormFlex was a pioneer in developing cultivation gutters that are formed on-site. They introduced the "AG plateau gutter," with suspension cables to reduce light interception. These systems resulted from the need for recirculation growing systems to conserve water and fertilizers. Leachate from the rockwool or coco coir slabs is collected by the raised gutters and conducted to a central system

FIGURE. 10.30 UV sterilizers on return solution. (From Eurofresh Farms, Wilcox, AZ. With permission.)

for treatment for disease control and nutrient and *p*H adjustment before returning to the crop. These raised gutters also offer advantages of optimum air circulation through the crop; improved working conditions for employees, with resultant increased labor productivity; and uniform water distribution between plants. They offer a complete range of gutter designs to best suit the specific crop grown.

Eurofresh Farms in Wilcox, Arizona and Houweling's Group, Camarillo, California use these FormFlex raised gutters for rockwool and coco coir systems. The raised gutter system is described in detail in Section 10.12.

Eurofresh Farms was one of the first greenhouse operations to introduce raised trays by FormFlex (Figure 10.31). They started a large trial in 2007 with rockwool culture. This system is now common in North America and Europe using coco coir slabs. They also introduced the principle of positive pressure cooling system by fans at one end of the greenhouse pulling air through a cooling pad and distributing the air under the plateau trays via a poly convection tube (Figures 10.31 and 10.32). This is now called the Ultra-Clima system. Refer to Chapter 12. The fans move cool air from the cooling pad or heated air from a hot water heat exchanger through the convection tube. It also serves to inject carbon dioxide into the greenhouse by the convection tube. With this system, they can heat or cool a greenhouse up to 200 m (656 ft) in length. The plateau trays collect the leachate from the slabs and return it for sterilization and EC and *p*H adjustment in the central injection room.

The raised trays also have supports for the plant stems as they are lowered so that the stems remain at or above the tray level (Figure 10.31). Heating pipes, even if not necessary for heating, are still placed in the aisles as "tracks" for the electric carts. This system is discussed further in Chapter 12.

10.10 INTERCROPPING TOMATOES

Eurofresh Farms intercrops plantings. The plants are pinched at 40 wk and removed at 47 wk. Before their removal, another crop is intercropped and allowed to reach about 3 ft (1 m) in height by the time of the removal of the previous crop. The new intercrop plants are set on new slabs beside the existing slabs by pushing them over on the collection tray. They plant four plants per slab, but each

FIGURE 10.31 Plateau gutters by FormFlex. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 10.32 Positive pressure cooling/heating greenhouse system. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 10.33 FormFlex plateau trays, with supports, convection tube, and irrigation line. (From Eurofresh Farms, Wilcox, AZ. With permission.)

plant is allowed to bifurcate to get the correct spacing of 3.3 plants per square meter (1 plant per 3.3 ft^2) and later increase stems to get 3.8 plants per square meter (1 plant per 2.8 ft^2).

The first cropping period is from July through March. They purchase 3-wk-old transplants. Production is from October through March. The second crop is interplanted by the middle of December and continues until July. It is intercropped on the same slabs as the first crop. The older plants are placed on one side of the slabs and the younger ones on the other side.

Flavorite in Warragul, Australia, trains the winter crop to double stems with three plants per rockwool slab. They use small "stubby" slabs that measure 50 cm x 24 cm x 10 cm thick. This gives six stems per slab. The intercrop plants are three plants per slab, but with three shoots (stems) per plant so the plant density is much higher during the summer crop (Figure 10.34).

Flavorite has 26 ha (64 acres) of greenhouses. The original houses of 3 ha (7.5 acres) are polyethylene structures. The second phase of expansion was 12 ha of venlo glass structures with 5 m gutters and the newest of 11 ha is a Van Der Hoeven venlo glass structure with 7 m high gutters and a "Modulair" positive pressure system with raised beds (Figure 10.35).

Intercropping requires four support wires. The older plants are strung on one set of two support wires and the younger plants on the second set of two support wires. Plants are V-cordon trained. When the first flowers form on the intercrop, the older crop is headed (growing tip is removed). After heading the older crop, leaves at the base of the plant are removed above the ripening fruit to allow light on the younger plants.

The drip irrigation lines are located next to the raised trays (Figure 10.33). The irrigation system is doubled so that one system feeds the young plants and the other feeds the mature plants (Figures 11.6 and 11.7). In this way, it is possible to set different irrigation cycles for each crop. However, this is only for the inlet drip lines, so the same formulation is used on all the plants, but the young plants get less cycles than the older ones.

This method of intercropping is particularly applied to high-sunlight regions such as southern California and Arizona. Both Houweling's Group, Camarillo, California and Eurofresh Farms (NatureSweet), Bonita, Arizona follow these practices. Intercropping saves on the use of the slabs (whether rockwool or coco coir) as two crops can be placed on the same slabs consecutively.

FIGURE 10.34 Intercropping of tomatoes on stubby slabs. Note: The left slab with the winter crop plants have 2 stems per plant, while the intercrop plants (right slab) have 3 stems. (From Flavorite, Warragul, Victoria, Australia. With permission.)

FIGURE 10.35 Modulair system with raised beds. Note: The intercrop plants between the stems of the older plants. (From Flavorite, Warragul, Victoria, Australia. With permission.)

Greenhouse operations in Australia, such as Flavorite, Warragul, Victoria, and Costa, Guyra, NSW, Australia having a lot of sunlight also intercrop. Flavorite intercrops the summer crop at about two months of age (Figures 10.34 and 10.35). This is done in early December. The older winter crop is started in February, transplanted in April and grows to the end of December.

As the relative humidity (RH) is very low in desert regions such as Arizona, the greenhouses must not be ventilated too quickly resulting in a sudden drop in the RH, which would stress the plants.

FIGURE 10.36 Machine to whitewash and wash the greenhouse roofs. (From Eurofresh Farms, Wilcox, AZ. With permission.)

For this reason, they shade the glasshouses with whitewash rather than a shade curtain during the summer months from March through September. They shade by airplane. They apply "ReduHeat" again in March and April to get 25% cooling. "ReduSol" is applied by airplane to remove the shade compound during the monsoon period. When the shade compound is removed by the end of September, the shade curtains are operated. They also clean the glass with a specialized cleaning machine to remove the desert dust (Figure 10.36). This is done by a night crew working every night to continually wash the glass year round.

Suckering of the plants is done specifically to retain RH in the greenhouse. Wilcox Greenhouses, an operation of 7.5 acres (3 ha), leaves two leaves on the suckers before pinching the growing tips. In some plants they prune all suckers in this way, while in others they leave two to three suckers per plant trained to two leaves. The number of suckers left depends on the plant growth characteristics, season, and RH. The suckers retain the RH in the crop canopy. The RH may be 75–80% inside the greenhouse, while it is only 8% outside. They stress that a lot of care must be taken with ventilation to prevent drying of the plants. They remove three leaves per plant per week as the plant grows three leaves per week. More leaves are kept on the plant during summer and more are removed during winter. Hot air is kept above the crop and air circulation is improved with 6 m (19.7 ft) gutters.

10.11 PEPPERS IN ROCKWOOL

Peppers are propagated similar to tomatoes. Seed is sown into rockwool cubes and seedlings transplanted to rockwool blocks. During germination, maintain temperatures 25–26°C (77–79°F) and RH from 75% to 80%. Maintain the same temperature during the day and night. Emergence occurs in 7–10 d. Use a dilute pepper nutrient formulation of 0.5 mS. After a week, as the seedlings emerge, reduce the temperature to 23–24°C (73–75°F). At the first-true-leaf stage, separate and space the seedlings to double the spacing and place them on their sides, similar to the tomatoes. This procedure is fine for small growers, but not feasible for larger growers. Also, if the peppers are grafted they must not be placed on their sides. Most large commercial operations also purchase their

FIGURE 10.37 Peppers transplanted to rockwool blocks.

seedlings from a specialized propagator as is done for the tomatoes. They are usually purchased at the 4- to 5-wk stage.

About 2 wk later (3 wk from sowing), transplant them to rockwool blocks of 7.5 cm x 10 cm (3 in. x 4 in.) dimensions. Similar to tomatoes, presoak the blocks with nutrient solution of EC 2.5 mS at 23°C (73°F). The peppers may also be laid on their sides when placing them in the blocks (Figure 10.37). This stimulates root growth to give better stem support. Maintain air temperatures at 24°C (75°F) during the day and 22°C (72°F) at night, with a 24-h average of 22°C (72°F). As for tomatoes, space the blocks apart as soon as the leaves start to overlap. Keep the RH at 70–75%. At 30 d, space the plants at 20 per square meter. Enrich with carbon dioxide at 800 ppm. Seedlings are transplanted to the greenhouse production area when they are from 5 to 6 wk old from sowing (Figure 10.38). The EC of the blocks should at that stage be from 3.0 to 3.5 mS. Four blocks per slab, each with one plant, will give similar spacing as for tomatoes.

As root temperatures are very important, it is best to propagate plants on slatted benches to provide good air movement, especially in more northerly climates where ambient temperatures are low during the propagation season. Piped hot water heating under the benches allowing heat to rise up through the plants is ideal.

Plant density for greenhouse production is between 8,000 and 10,000 plants per acre (20,000 and 25,000 plants per hectare). That is equivalent to 3.3–3.5 plants per square meter of greenhouse area. This is similar to that of tomatoes. As the peppers are trained to two stems each, this density increases to 6.5–7 stems per square meter.

If the rockwool slabs are placed as two rows (double), locate three plants per slab, whereas, in a single row use five plants per slab. Most growers use the single-row method with more plants and V-cordon them overhead. Spacing between two single rows is 40 cm (16 in.) and 1.46 m (57 in.) between the drainage/irrigation lines. Slabs are spaced 23 cm (9 in.) apart within each row if the slabs are 100 cm (39 in.) in length. For a single-row configuration, rows are 1.8 m (71 in.) apart, and the slabs placed together end to end within the row. With V-cordon training to the upper support

FIGURE 10.38 Pepper at 39 d ready to be transplanted.

cables the final plant density regardless of the row configuration is from 3.3 to 3.5 plants per square meter of greenhouse floor area.

Once good rooting into the slabs has become established and shoot growth has reached 40 cm (16 in.), the temperature regime should be reduced to 18–19°C (65°F) at night and 22–23°C (72°F) by day. A vigorous crop will tolerate day temperatures as high as 30°C (86°F) in full sunlight, but temperatures of 35°C (95°F) or above will be harmful.

Pepper seedlings should be approximately 25 cm (10 in.) tall with at least six leaves on the main stem when transplanting to the slabs. Presoak the slab with nutrient solution of EC 2.5–3.0 mS for 24 h before transplanting. Soak the slabs well by placing three to five drip lines in each before cutting drainage holes in them as was described earlier for European cucumbers. After the slabs are thoroughly soaked, cut the drainage holes in them. Cut about 2-in.-long slits between the plants at an angle to the bottom of the slab to allow complete drainage. Today, most growers use the Formflex or equivalent collection trays to support the slabs to enable the nutrient solution to be recycled. If the solution is not recycled, it can be drained to a large outdoor reservoir for use on field crops or pastures during the summer months in the northern climates. Since peppers are not lowered and leaned during their cropping cycle, collection trays are raised only slightly above the floor in order to allow for their extra height (Figure 10.39). Flavorite, Warragul, Australia, places four plants per regular slab. They allow each plant to bifurcate once or they may plant two plants per block if not permitting them to bifurcate.

For the first week after transplanting, maintain the greenhouse at day/night temperatures 20–21°C (68–70°F) and CO_2 concentration at 800–1000 ppm. Establish the plants with a strong root system. The EC of the feed solution should be 2.5–3.5 mS, with the slabs at EC 3.5–4.0 mS. The optimum temperature for vegetative growth is 21–23°C (70–73°F) and for production, about 21°C (70°F) (Bakker 1989).

FIGURE 10.39 Four blocks per slab with either two non-bifurcated plants or one bifurcated plant per block to give a total of eight stems per slab. (From Flavorite, Warragul, Victoria, Australia. With permission.)

In British Columbia, the growers seed peppers on October 1 and transplant to the rockwool slabs by early December, with the first harvest by early March. Harvesting continues until mid-November.

Greenhouse peppers are trained vertically with two stems in a V-cordon form. They must be pruned correctly to keep them in balance between vegetative and generative growths. Train peppers at least every 2 wk.

About 1–2 wk after transplanting, the peppers will form two to three stems. If three stems form, prune out the third stem, leaving only the strongest two stems. Each stem will grow to about 4–5 m (13–16 ft), supported by overhead cables and string. One string is needed per stem. Attach one string just below the bifurcation of the main stem early after transplanting and then later attach a second string to the second stem on initial pruning (Figure 10.40). Secure the support string with plastic stem clamps just under the side shoots as they develop.

Where the stem first bifurcates a "crown" flower will form. This flower bud can be removed to keep the plant more vegetative initially. However, if your climate favors rapid vegetative growth and the plants are strongly in that phase, leave the crown flower on to help shift the plant toward being generative. In general, it is recommended to remove the flowers at the first and third nodes, but this again is determined by the amount of sunlight. Under high sunlight conditions, allow these fruit to develop. Allow two leaves on the side shoots (laterals) before cutting the tip (Figure 10.41). Be careful to maintain the strong main stem. If by mistake or other damage it should be terminated, allow a strong side shoot to take over as the main leader. Usually, one fruit will develop at each side shoot, but often a second will set along the side shoot. Do not permit any more, or the side shoots will break. Training of peppers and other crops is discussed in more detail in Chapter 16.

10.12 RECIRCULATING ROCKWOOL SYSTEMS

With increasing pressure due to public awareness of the environment and water as a natural resource, it has become important to conserve water and minimize any runoff of fertilizer-enriched solution. In countries such as Holland with a high population and a large greenhouse industry using large volumes of water, the recirculation of nutrient solutions in hydroponic systems is imperative. One of

FIGURE 10.40 Clamp the main stem of the peppers just below the bifurcation.

FIGURE 10.41 Cutting of side shoots at second leaf and clamping pepper.

the earliest forms of recirculation rockwool cultures is the use of plastic semirigid channels in which the rockwool slabs are contained. There are a number of manufacturers of these channels. Some may be used as NFT systems as well as with rockwool.

These channels come in rolls, which, when unwound, form a channel by staking the sides upright with special clamps. The ends are folded up and stapled. A special drain-pipe adapter is fitted onto the return end of the channel. PVC piping conducts the solution back to a nutrient cistern. Each plant is irrigated with a drip system as discussed above. It is important that the channel is about 0.5 in. (~1–2 cm) wider than the slabs to allow flow of the drain water past the slabs.

A common channel used now is that by FormFlex, as was discussed earlier. These gutters are available in the lower ones raised slightly above ground level and the plateau trays that keep the return channels raised at about waist level to facilitate working with the plants. The raised plateau trays permit the heating/cooling convection tube to be located below it. The trend now is to use the plateau trays to get better air circulation and more efficiency in workers' time for carrying out their tasks with the plants. The earlier lower level trays are shown in Figures 10.42 and 10.43. The FormFlex gutters all have collection channels on the sides to return the water to storage tanks for treatment in the injection area of the greenhouse. The "AG" gutter by FormFlex is the international standard for vegetable crops. It is available in numerous widths and styles for specific crops. The "LG" gutter is specifically for growing sweet bell peppers. It has high stability and draining capacity. They manufacture 13 types of gutters with various configurations for use with specific vegetable and flower crops. Most of these gutters are now used in combination with the plateau trays, especially with the climate control convection tubes below (Figure 10.44). The convection tubes have small holes in their sides for air and CO_2 to exit (Figure 10.45).

Unlike the lower gullies that had Styrofoam insulation underneath to maintain optimum root temperatures, the plateau trays do not need the Styrofoam as root temperature in the slabs can be controlled by the temperature of the air from the convection tube below the FormFlex or other recirculation trays. Regardless, of whether the trays are the plateau or lower ones, the slope of the slabs can be evenly graded by the adjustment of the raised frame supporting the trays. A slope of 1–2 in.

FIGURE 10.42 FormFlex "AG" gutter. Note: The collection channel on each side and the location of the irrigation lateral with drip lines. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 10.43 Very productive crop of "Brilliant" TOV tomatoes. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 10.44 Raised trays above the convection tubes. Note: The small holes in the sides of the convection tubes for air movement. (From Flavorite, Warragul, Victoria, Australia. With permission.)

(~2.2–5 cm) is adequate for drainage as the side collection channels are free of any roots or debris. Several holes between the plants in the slab wrapping will provide good drainage. Runoff from the slabs is vertically away from the base of the slabs into the side drainage troughs of the tray. This gives good aeration of the slabs. The solution is recirculated from the drain channels of the tray at the end through a 1.5-in.-diameter PVC drain pipe connected to an underground 4-in.-diameter

FIGURE 10.45 The convection tube runs the entire crop row length to the central aisle. Note: The small holes in the convection tube sides for release of the air and CO_2. (From Flavorite, Warragul, Victoria, Australia. With permission.)

collection pipe to the nutrient tank. Solution is applied to each plant individually through a drip irrigation system (Figure 10.42).

The return solution is collected in a cistern and then pumped up into an above-ground nutrient return tank. Large particles are removed from the solution by a separator, followed by a filtration system (usually sand filters in large operations) before the solution enters the return tank (Figures 10.46 and 10.47). The solution is also sterilized before it enters the return tank. Sterilization may be by one of several methods: heat treatment, ozonation, UV (Figure 10.30), or hydrogen peroxide. Hydrogen peroxide is now becoming the most popular method. The return tank solution is then pumped to a batch tank where the EC and *p*H are monitored and adjusted by an injection system. This is controlled by a computer system such as Priva or Argus, which monitors these data and on a feedback basis with preset levels for the EC and *p*H allocates the volumes of the injector stock solutions that are added to the batch tank. From there, the solution is pumped back to the plants in the greenhouse through the drip irrigation system.

The nutrient return and batch tanks must be of sufficient volume for at least one day's supply for the plants (approximately 1 L/ft^2/d). The irrigation system, therefore, consists of an injector system operated by a computer monitoring the EC and *p*H, pumps, sand filters, sterilization system, and emitters at the plants. Locating the emitters on the poly lateral line instead of at the ends of the drip lines will help.

Nutrient analyses of both feed and drain solutions provide data on which to base adjustments of the solution. This must be done weekly. The returning solution has to be diluted with raw water to make up the loss in volume by the uptake of the plants. This decreases the EC level and changes the *p*H. If the raw water is coming from wells, it should be treated with hydrogen peroxide to eliminate potential fungal and bacterial infections. Water can be pumped to a pretreated tank and then be sterilized before entering a supply tank from which it is drawn as makeup water. The computer monitoring the EC and *p*H adds stock solutions and acid to bring these factors back to a preset level. However, as discussed in Chapter 3, EC measures total dissolved salts (TDS), not the levels of individual ions.

FIGURE 10.46 UV sterilizer and sand filters. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 10.47 Sand filters with return tank. (From Eurofresh Farms, Wilcox, AZ. With permission.)

Nutrient-solution analysis is imperative to enable the grower to make changes in the composition of the nutrient solution to keep it within optimum levels.

10.13 ADVANTAGES AND DISADVANTAGES OF ROCKWOOL CULTURE

The advantages of rockwool culture are as follows:

1. As an open system, there is less chance for disease to spread throughout the crop.
2. There is uniform application of nutrients to the plants; each plant is fed individually.
3. Since rockwool is light, it can easily be handled.
4. It is simple to provide bottom heat.
5. It is easily steam sterilized if the grower wishes to use it several times. Structurally, it will not break down for up to 4 yr.
6. Rapid crop turnaround is possible at minimal labor cost.
7. It provides good root aeration.
8. There is less risk of crop failure due to mechanical breakdown in the system than with NFT.
9. Little growth setback occurs during transplanting.
10. It requires less capital cost for equipment and installation than many NFT systems.

The disadvantages of rockwool culture are as follows:

1. Rockwool is relatively expensive in countries not manufacturing it locally.
2. Accumulation of carbonates and sodium may occur in the rockwool slabs in regions having high salts in the raw water. In such areas, a reverse osmosis water purifier would be required.

Overall, rockwool culture offers many positive factors in the growing of not only vine crops, but also cut flowers such as roses and potted flowering plants. It is also widely used as a propagation medium for vegetables such as lettuce, spinach, and other low-profile crops.

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11 Coco Coir Culture

11.1 INTRODUCTION

With increased environmental pressures on greenhouse operations to use sustainable or renewable resources, coco coir is quickly expanding as the newest environmentally safe substrate. Many large hydroponic greenhouse operations worldwide have converted to coco coir as their preferred substrate. Houweling's Group, Camarillo, California, expanded by 40 acres (16 ha) in 2009 and initiated the use of coco coir in the new greenhouse. Houweling's Group now uses coco coir in all their operations including the new 28-acre (11-ha) facility built in 2014 in Mona, Utah. Many growers in B.C. and Ontario have done the same. Many of the growers initially used coco coir for tomatoes, but now have converted to coco coir for peppers and eggplants. According to a 2009 publication, *Grow-How* by Van der Knapp-Braam, B.V., who make coco coir products coming from Sri Lanka under the name Forteco, in 2008 stated approximately 70 ha (175 acres) of tomatoes and sweet peppers were grown on Forteco coco peat slabs in Mexico. One grower in Poland, Mularski Nursery, has 56 ha (140 acres) of tomatoes with coco coir substrate (Lindhout, 2010). In 2006 they converted the entire operation from rockwool to Forteco coco coir.

11.2 SOURCE OF COCO COIR

Coco coir comes from ground-up coconut palm (*Cocos nucifera*) husks after they have dried (Anonymous, 2011). Coco coir is not screened to remove the fibers, so this adds to its porosity and gives better aeration than peat moss. The components of the coconut fruit are in layers from the outside to the inside and include the exocarp, mesocarp, endocarp, endosperm, and embryo (Gunn, 2004). The endosperm is the white edible part of the coconut and the liquid. The husk consists of an outer skin (exocarp), middle hard layer (mesocarp), and the shell (endocarp). The testa is the seed coat located between the shell and the meat (endosperm).

Coir is the fiber from the husk. The fibrous strands are used to make brushes, doormats, nets, and twine. The husk can be separated into coir fibers and coir pith or pulp, a coir dust that has been a waste product. This coir pith is biodegradable, but can take up to 20 yr to decompose. Research in the 1980s developed a process to transform coir pith into a medium used in mulching, soil treatment, and hydroponics, where it can be used as a substitute for peat moss and vermiculite.

The largest coconut producers include the Philippines, Indonesia, India, Brazil, Sri Lanka, and Thailand. The coconut shell consists of (dry basis) 34% cellulose, 36.5% lignin, 29% pentosans (five-carbon sugars), and 0.6% ash (Woodroof, 1979).

11.3 COCO COIR GRADES AND CHARACTERISTICS

Forteco BV., a subsidiary of the Van der Knapp group companies, has headquarters in Holland, but production facilities in Sri Lanka and India, where they source their coconut husks. They also have a research center in Holland where they test new coco coir products, such as plugs, blocks, discs, and slabs in various crop trials.

Forteco has developed four different coco slabs, each having characteristics to steer toward generative or vegetative growth of specific crops. The "Forteco Basic" slab steers toward the vegetative phase, with an air-holding capacity of 20% at full water saturation. It is composed of coco pith. The "Forteco Power" slab is suited for generative and vegetative steering and has 25% air-holding capacity at full saturation. It is composed of crushed husk and coir pith. The "Forteco Profit" slab is for

DOI: 10.1201/9781003133254-11

generative growth, with 30% air capacity at saturation. It is made from crushed husk and is buffered. Lastly, the "Forteco Maximum" is for maximum generative growth, having 40% air capacity at saturation. It is composed of buffered crushed husk.

Forteco slabs are "ready to use," with drain slits and precut plant holes. The company claims that because of the unique air/water ratio, plant roots grow evenly throughout the substrate. They claim that the homogenous nature of the substrate gives excellent growing, resulting in maximized yields.

Forteco has designed weighing scales that monitor the weight of the slabs at 1-min intervals and send the data to the computer controller that analysis and regulates irrigation cycles. With this data, irrigation cycles are refined to also decrease the moisture content of the slabs during night. This type of feedback system for irrigation control was discussed in Chapter 10. Coco coir slabs are very stable and are therefore suitable for several years of crop cultivation. Since they are 100% organic, they may be completely recycled as a soil conditioner.

In the tropics, coco coir can be purchased very cheap by the truckload in bulk form. However, a number of companies in North America compress it into an expandable hard brick. By adding 5 qt (5 L) of water to each brick of 20 oz (567 g), it expands to approximately 9 qt (9 L) within 15 min. It has a fluffy texture, with a *p*H of 5.7–6.3. One precaution to observe is to check its sodium chloride content, especially if purchasing bulk coco coir from coastal areas close to the ocean.

Coco coir may be mixed with perlite or vermiculite in similar ratios, as is discussed later for peat in peat-lite mixes. It can also be used as a mixture with rice hulls, as is discussed later in Chapter 15.

The high cation exchange capacity (CEC) of the cellulose in coir traps cations from the solution and releases them at root absorption. Cations are positively charged atoms and minerals dissolved in solution, such as K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Mn^{2+}, Cu^{2+}, Zn^{2+}, and B^{3+}. These were discussed in detail in Chapter 3. Coir has a higher *p*H than peat moss. The cellulose and lignin's in coir are highly electronegative molecules that absorb or "trap" cations. So, the absorptive capacity of coir is high, with a very large surface area in the granular structure of the coir. These absorbed cations will exchange for other cations in solution. The CEC changes with *p*H since H^+ is a very small cation and is also attracted by the cellulose in coir.

Jiffy Products make coco coir blocks wrapped with a fine capillary fleece that are similar in shape and size to rockwool blocks (Figures 11.1, 11.4, and 11.5). They claim that their coco "Growblocks" are 100% pathogen free and that with the presence of antagonistic bacteria in the substrate they suppress *Pythium* fungal infection of plant roots. Jiffy is now making coco coir slabs (Jiffy Growbags). They have four sizes to suit the gutter or raised tray channels.

All growbags are 100 cm (39.4 in.) in length, but their width and height vary according to the gutters in which they are to be located. For small gutters or low-volume systems, Jiffy Products recommend width of 15 cm (6 in.) and two possible heights (8 cm or 3 in. for low volume and 10 cm or 4 in. for moderate volume). For wider gutters or high-volume systems, they created a 20-cm (8-in.) width, and heights of 8 cm (3 in.) and 10 cm (4 in.) for moderate and large volume systems, respectively.

They also have three substrate characteristics to best suit specific crops. Their "Jiffy Premium Growbag" is a double-layered substrate with 50% husk chips and 50% coco pith, used for tomatoes and peppers in all climates (Figure 11.2). The "Jiffy HC Growbag," which is 100% husk chips, is for cucumbers in moderate climates. The "Jiffy 5050 Growbag," which has a uniform mixture of 50% husk chips and 50% coco pith, is for rose and strawberry growing in Mediterranean climates (Figure 11.3).

11.4 COCO PLUGS AND BLOCKS

At present, most growers using coco slabs seed into rockwool cubes or Kiem plug trays using small plugs, Growcubes, or granulate rockwool. Each Kiem plug tray has 240 rockwool plugs that are

FIGURE 11.1 Jiffy Growblocks on Jiffy Growbag with peppers. (From Jiffy Products. With permission.)

FIGURE 11.2 Jiffy Growbag showing root growth. (From of Jiffy Products. With permission.)

suitable for sowing seed and later transplanting to rockwool blocks or coco blocks. The Growcubes are 0.25-in. (0.7-cm) cubes of rockwool.

Jiffy Products make coco coir plugs, blocks, and slabs. Jiffy coco coir plugs are 3 cm x 3.5 cm deep (1.2 in. x 1.4 in. deep) on soaking with water. They also make grow blocks with a single hole to fit either their plug or rockwool plugs. These blocks are composed of pithy tissues of coconut husks manufactured in Sri Lanka. They claim that they hold slightly less water than rockwool blocks in order to promote early root growth. The coco substrate is stable and will not degrade during the growing cycle. The coco coir is wrapped in a biodegradable fine capillary "fleece" to contain the coco coir so that the coco substrate will not enter the hydroponic system during the cropping period.

FIGURE 11.3 Strawberries growing in coco coir in raised gutter. (From Jiffy Products. With permission.)

They come in two sizes, 7.5-cm (3-in.) and 10-cm (4-in.) blocks with holes that will contain their Jiffy-7C coco coir plugs or rockwool plugs. They are now also making double blocks to contain two plants (Figures 11.4 and 11.5). When water and nutrient solution are added to the blocks, they expand to their full size and are then ready for transplanting seedling plugs.

11.5 TOMATOES IN COCO COIR

Houweling's Group starts their seedlings in their British Columbia nursery. They green graft the tomatoes to vigorous, disease-resistant rootstocks and ship them to their California operation at 5 wk. The Camarillo operation uses coco coir slabs. The tomato seedlings are transplanted to mini coco coir slabs. Each slab normally has two blocks of double-stem seedlings or two blocks with two tomato plants each, so the total stems per slab is four. When intercropping, the slab will contain four blocks, two blocks with the older bifurcated plants and two blocks containing two plants each for the intercrop. For more information on intercropping refer to Chapter 10, Section 10.10.

The slabs are set on top of a FormFlex raised gutter that recirculates the solution. The large convection tube underneath the raised gutter circulates the air, adds carbon dioxide, and maintains optimum temperatures as described in Chapter 10.

Tomatoes are intercropped, so there are two irrigation systems (Figures 11.6 and 11.7). One system is for the mature plants, and the other is for the young plants. In this way, it is possible to set different irrigation cycles for each crop. However, this is only for the inlet drip lines, so the same formulation is used on all the plants, but the young plants get less cycles than the older ones.

FIGURE 11.4 Double Jiffy Blocks with tomatoes. (From Jiffy Products. With permission.)

FIGURE 11.5 Base of Jiffy Block showing extensive, healthy root growth. Note: The "fleece" net wrapping. (From Jiffy Products. With permission.)

FIGURE 11.6 Two inlet irrigation systems to the crops for intercropping. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 11.7 Drip line inlet laterals, two per growing tray for intercropping. (From Houweling's Group, Inc., Camarillo, CA. With permission.)

FIGURE 11.8 New seedlings for intercropping are brought from British Columbia. (From Houweling's Group, Camarillo, CA. With permission.)

In the case of Houweling's, Group, they start their plants in their British Columbia nursery operation. They graft the tomato-on-vine (TOV) variety "Success" to Maxifort rootstock. The grafted seedlings are shipped by truck to Camarillo when the plants are about 5 wk old (Figure 11.8). The new plants are planted between the existing ones on the same slabs or on new slabs placed between the slabs of the mature plants (Figures 11.9 through 11.11). The older plants have the lower part of their stems de-leafed as the fruit is harvested. This permits light to enter to the younger intercrop. When the intercrop plants are within a week or so of starting to produce fruit the older plants are removed (usually about 9–10 wk after transplanting the intercrop). The intercrop is trained by string on tomahooks to the inside two of the four support wires. When the old crop is removed, the intercrop hooks are placed onto the outside two wires so that the plants are trained in a V-cordon fashion.

The training of the plants in coco coir is the same as with rockwool, as discussed in Chapter 10. The main difference between coco coir and rockwool cultures is the nutrient management. Less frequent irrigation cycles are needed because of the greater water retention of the coco coir.

11.6 ADVANTAGES AND DISADVANTAGES OF COCO COIR CULTURE

Advantages of coco coir are as follows:

1. This is a closed system to conserve water and fertilizers.
2. Coco slabs have high air-holding capacity, which is important in steering the crops.
3. With good capillarity, the slabs can be dried more than rockwool to permit easy steering of the crops.
4. When the slabs are dried, they easily reabsorb adequate water without any remaining dry spots, as can occur with rockwool.
5. Coco slabs come in different proportions of fine pith material to fibrous material or husk chips to best suit specific crops. Most slab producers have at least four grade types.
6. Owing to the unique air/water ratio, roots easily penetrate and grow throughout the substrate.

FIGURE 11.9 Mini coco coir slabs. Slab on the left has two mature plants with two stems per plant, while the one on the right has two mature plants and two seedlings recently transplanted. The older plants will be removed as the young ones approach maturity. (From Houweling's Group, Camarillo, CA. With permission.)

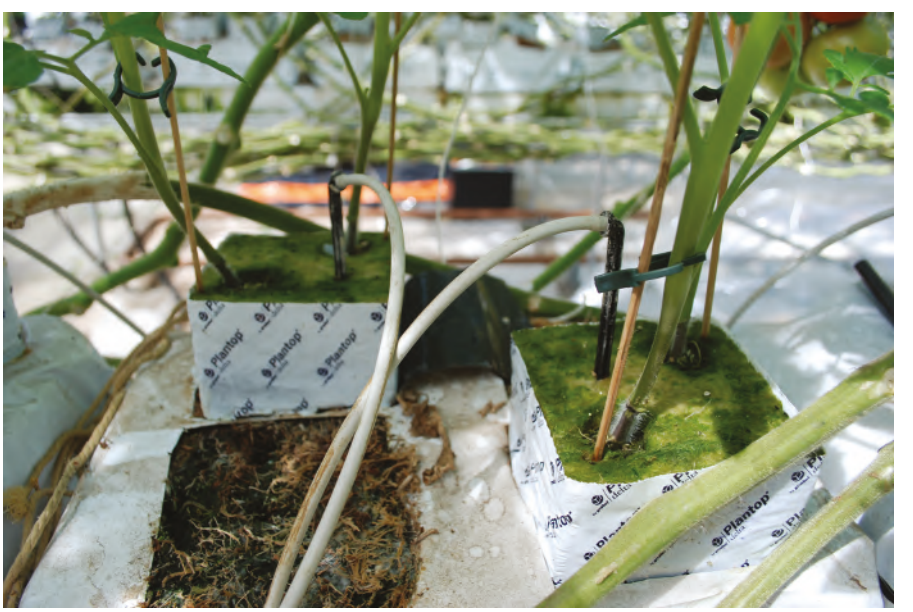

FIGURE 11.10 A mini slab with two recently transplanted blocks, each with two seedling plants. Note: The older plants were removed to permit more light to the young transplants. (From Houweling's Group, Camarillo, CA. With permission.)

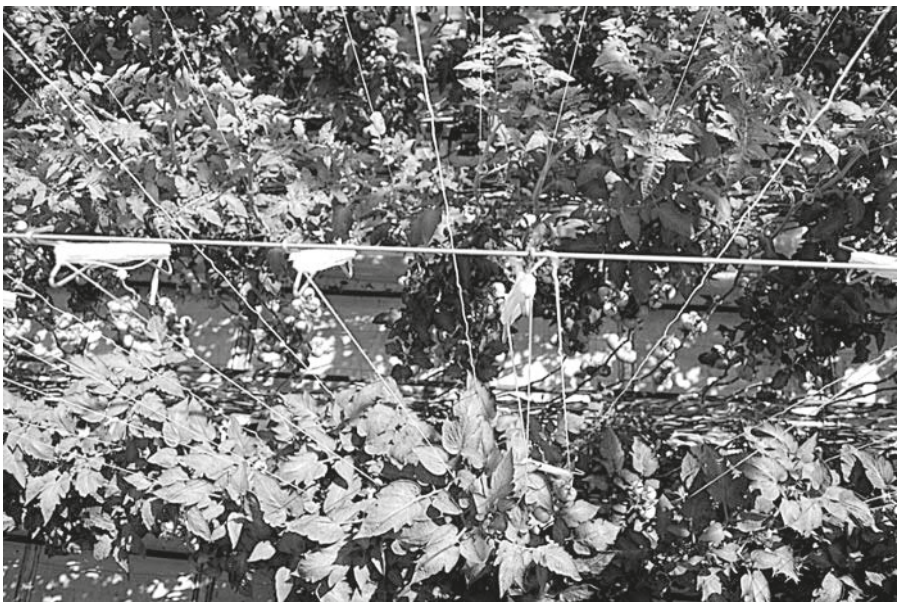

FIGURE 11.11 Intercrop of tomatoes. Note: The younger plants in the lower portion of the photo and the older crop above it. (From Houweling's Group, Camarillo, CA. With permission.)

7. Coco slabs are very stable and can be used for more than one season.
8. Coco is 100% organic and can easily be recycled as a soil conditioner. It does not create a disposal issue with landfills as does rockwool.
9. Coco substrates maintain antagonistic bacteria and can be inoculated with other beneficial microorganisms to reduce risk of fungal diseases caused by organisms such as *Pythium*.

The disadvantages of coco coir culture are as follows:

1. As coco coir is used with closed systems, if the return leachate is not treated adequately against disease organisms, pathogens could build up in the substrate.
2. Some coco coir, if not leached adequately by the manufacturer, could contain high levels of sodium chloride that must be leached by the grower. Most coco producers state that their product is free of such salt.
3. Coco coir may contain potassium. If so, the grower needs to adjust the nutrient solution accordingly and flush the slabs with a low potassium nutrient solution.

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12 Greenhouse Environmental Control and Automation

12.1 INTRODUCTION

Hydroponic growing is applicable to both indoor and outdoor environments. However, in most regions of the world the ambient environment is often not favorable to growing many of the crops generally grown hydroponically. Temperate climates have extreme differences of conditions from one season to another and are prohibitive to growing outside year round. Other arid areas have excessive temperatures that reduce crop production greatly, so a greenhouse structure is needed to control non-optimal temperatures and high light conditions. In tropical climates where temperatures are acceptable to many vegetable crops, extreme humidity, rainfall, pests, and diseases make growing outside very challenging, resulting in reduced yields. Capital costs of hydroponic growing systems are high, so production must be maximized to make them economically viable. Crop production must be year round, not just seasonal. In order to accomplish continual production a protective structure providing as close as possible optimum growing conditions through controlled environmental agriculture (CEA) is an integral part of hydroponic growing. Greenhouses are that component required for hydroponic culture permitting annual production. By providing optimum environmental conditions for the specific crops grown, maximum yields and high quality of produce is achieved.

Modern greenhouses control temperatures, relative humidity (RH), light intensities with shade curtains and now LED supplementary lighting, carbon dioxide enrichment levels, irrigation cycles and duration, nutrient solution recycling, nutrient solution adjustments, raw water and nutrient solution sterilization. Movement of plants into the growing area and to packing facilities during harvesting is done with self-directed carts or other mechanical methods. Many steps in the grading and packing of products are automated. Environmental factors are controlled through an ambient weather station and computer system monitoring all factors and making adjustments to these factors by feedback systems. Presently, many robotic systems are being developed to train plants and harvest the finished products.

Solar panels may be used to generate electricity and some large commercial greenhouses are located near power plants in order to use waste heat from those operations. Such co-generation projects are becoming common. In some areas geothermal heat can be part of a greenhouse operation. New technology over the past decade has developed cogeneration called “combined heat and power” (CHP) using a reciprocating engine to generate electricity and produce heat and carbon dioxide enrichment at the same time. The engine is powered by natural gas that emits clean carbon dioxide.

The methods of controlling environmental factors and greenhouse automation systems are discussed in this chapter.

12.2 TEMPERATURE

Temperature regulation includes heating and cooling to maintain optimum growing ranges. Different greenhouse vegetable crops require specific day and night optimum temperature ranges as well as temperature differentials. Relative humidity (RH) is closely related to temperatures.

DOI: 10.1201/9781003133254-12

As temperatures rise RH falls and vice versa as temperatures fall RH rises with specific moisture levels of the air. Heating systems are basically of two types, central heating and individual house or range heating. A central heating system is one composed of hot water heat by usually gas fired boilers distributed throughout the greenhouse by black iron piping. Individual heating units within the greenhouse is by unit heat exchangers and distribution by convection tubing and/or horizontal air flow (HAF) fans.

Optimum temperature ranges vary with specific crops, stages of plant growth (seedling, transplant, and mature growth phases), and light conditions (Table 16.1). Temperatures also assist in steering vegetative versus generative growth phases in fruiting crops, such as tomatoes, peppers, eggplants, and cucumbers (Tables 16.2 and 16.3).

The function of the greenhouse is to maintain these optimum temperature ranges for the crops. This is achieved by computer controls with sensors in the greenhouse and a weather station adjacent to or attached to the greenhouse roof. This weather station gives constant information that is logged by the computer system. Typical information provided includes temperature, relative humidity, precipitation in form of rainfall and snowfall, sunlight intensity, wind speed, and direction. This ambient information is linked to the greenhouse environmental conditions and the computer sends inputs to the appropriate systems to make adjustments in these conditions to meet close as possible optimum levels.

12.2.1 Heating Systems

The two principal heating systems in greenhouses are central boiler hot water and individual range unit heating. Large commercial greenhouses use central natural gas fired boilers (Figure 12.1), which heat water to usually 180°F (82°C) without pressure, that is distributed throughout the greenhouse in pipes. These pipes located in the plant row aisles, are called tube rails as they loop in the aisles and provide "tracks" on which carts run for the training and harvesting of the plants as shown in Figures 9.4 and 9.5). In cold climates a hot water pipe is located within the crop row. This "grow tube" is raised or lowered within the crop to maintain optimum temperature near the flowers and

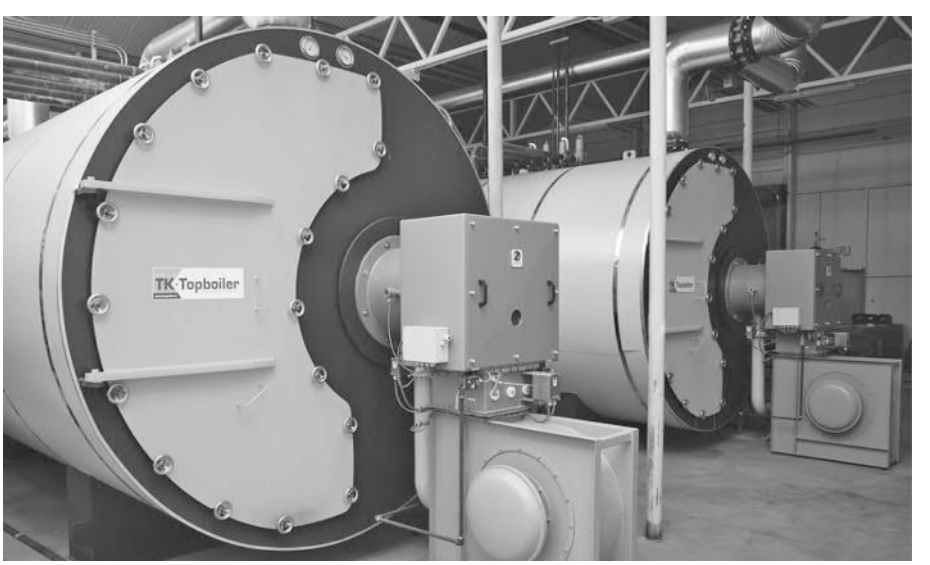

FIGURE 12.1 Natural gas fired hot water boiler. (From Prins Greenhouses, Abbotsford, BC, Canada. With permission.)

FIGURE 12.2 Crop grow tube heating. (From Prins Greenhouses, Abbotsford, BC, Canada. With permission.)

FIGURE 12.3 Perimeter hot water heating pipes and perimeter wall screen. (From Prins Greenhouses, Abbotsford, BC, Canada. With permission.)

fruit development to assist in controlling the fruiting and ripening process (Figures 12.2 and 10.43). Black iron pipe is used for the tube rails and other piping from the boiler. Heating pipes may be used next to perimeter side walls in vertical banks of 2 to 4 pipes high to heat areas of high heat loss (Figure 12.3).

Carbon dioxide enrichment of the crop significantly increases production. Carbon dioxide in large commercial greenhouses is generated by the waste heat from natural gas fired boilers that have

FIGURE 12.4 Hot water storage tanks. (From Houweling's Group, Camarillo, CA. With permission.)

high combustion efficiency. Operating the boilers during the day to generate the carbon dioxide produces excess heat. During the day the heated water may not be needed in heating the greenhouse, especially during summer months, so the heated water is stored in million-gallon storage tanks (Figure 12.4). This heated water at night, when heat is required, is pumped back through the boiler and its temperature raised by the heat differential needed to circulate it through the greenhouse piping.

More recent updated central heating systems use boilers that heat water for distribution through the greenhouse to heat exchangers in a chamber at the greenhouse end walls. The greenhouse cooling pad is covered with an insect screen to prevent insects from entering (Figure 12.5). This heating-cooling is called an "Ultra-Clima" system (Figures 12.6 and 12.7). This system functions to heat, cool, dehumidify, and inject carbon dioxide into a closed greenhouse (Figure 12.8). Positive pressure is created by large fans located within the chamber blowing air into large convection tubes located under the raised trays supporting the vine crops (Figures 10.31, 10.44, 10.45 and 12.9 through 12.11). For heating the heat exchangers use hot water piped from the central boiler heating system. The atmosphere is constantly recirculated by the use of overhead horizontal airflow fans and the large polyethylene convection tube located under the raised growing trays. The system is capable of heating or cooling a greenhouse up to 200 m (656 ft) in length.

Large screened roof vents reduce light entering the greenhouse by 15% or more, especially if not kept clean. With the Ultra-Clima system roof vents are reduced by 90%, thus increasing light levels into the greenhouse by 16% according to claims by KUBO greenhouses (KUBO Greenhouse Projects, www.kubogroup.nl/en). The vents are needed only to release pressure in the greenhouse so that excess pressure does not break the glass. The roof vents are screened to prevent insects (Figure 12.12). With positive pressure inside the greenhouse insects are kept away from the vents. The reduction of roof vents also reduces the loss of carbon dioxide that is injected into the convection tubes of the air circulation system.

Kubo claims (2020) that they have developed over 700 hectares (1730 acres) of Ultra-Clima greenhouses worldwide. This Ultra-Clima technology is part of sustainable agriculture.

FIGURE 12.5 High sidewalls of Houweling's Group greenhouse. Note: The insect screen covering the entire end. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 12.6 Evaporative cooling pad above on the right, glass shutter directly above. Note: The shutter is fully open for cooling cycle. Hot water mains on the left. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 12.7 Cooling pad on upper left; on the right are the heat exchangers in the fan housing. (From Houweling's Group, Camarillo, CA. With permission.)

12.2.2 Sustainable Agriculture Greenhouse Technology

In 2009, Houweling's Group, constructed a new 16-ha (40-acre) greenhouse range for growing tomatoes in coco coir (www.houwelings.com).

The greenhouses use the most recent advances in technology, making this operation one of the most high-tech greenhouses in the world. It includes 4 acres (1.6 ha) of solar panels to generate electricity for the new range. Houweling's terms this new greenhouse range, "Future of Sustainable Agriculture" greenhouses (Schineller, 2009). The greenhouses are a Dutch Venlo type of glass structure manufactured by KUBO Greenhouse Projects (www.kubogroup.nl/en) of the Netherlands. The greenhouse sidewall height is 7 m (23 ft) to permit the hot air in the greenhouse to rise above the plant crop (Figure 12.5). This height also gives better air circulation than lower structures of the same nature. Above are small vents with bug screens to prevent insects from entering. Air circulation, heating, cooling, and carbon dioxide enrichment are all based on positive pressure.

American Capital Energy (www.AmericanCaptialEnergy.com) worked with Houweling's to provide electric power and stored heat to power and warm the greenhouse operation. The solar unit is a 1.1-MW solar photovoltaic system mounted on a tilting rack located over a 4-acre water-retention pond (Figures 12.13 and 12.14). The tilting design positions the panels to maximize sunlight interception. The solar thermal heat system heats the water in the retention pond below to reduce the overall heating costs of the greenhouse during the night. The system is projected to provide over 50% of the facility's energy needs.

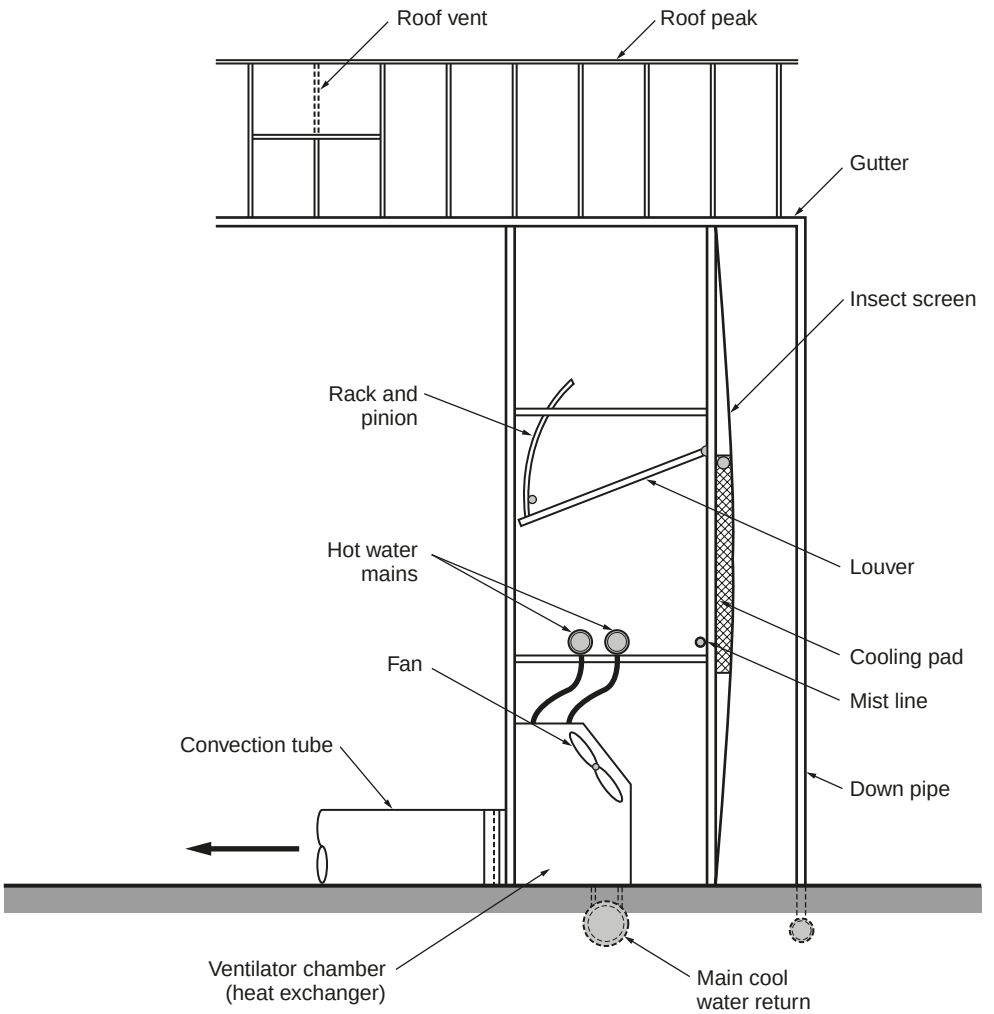

FIGURE 12.8 Drawing of Ultra-Clima System. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

Argus Control Systems Ltd., White Rock, British Columbia (www.arguscontrols.com), provided climate control systems to closely monitor and adjust all environmental and irrigation systems to optimize conditions for plant growth and efficient use of greenhouse systems to reduce production costs.

This greenhouse operation is a semi-closed, positive pressure greenhouse that improves insect exclusion, reduces disease, reduces water and fertilizer use, and enhances efficiency in carbon dioxide enrichment. According to Casey Houweling, the owner, the closed greenhouse environment reduces evaporation of irrigation water. The excess irrigation leachate is collected by FormFlex raised growing gutters and is transported to a water treatment system.

Treatment and recycling of condensation, rain, and runoff water, and fertilizing nutrients are accomplished through a system designed by Pure-O-Tech of Escondido, California (www.pureotech.com), that involves filtration and ozonation.

Water is heated by the solar thermal array and warehouse refrigeration exhaust heat, stored in million-gallon hot water storage tanks, and circulated through the system, especially at night. The

FIGURE 12.9 Connection of heating/cooling convection tube to fan housing. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 12.10 Raised growing trays with polyethylene heating/cooling convection tube below. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 12.11 Raised growing tray with the heating/cooling convection tube below. (From Houweling's Group, Camarillo, CA. With permission.)

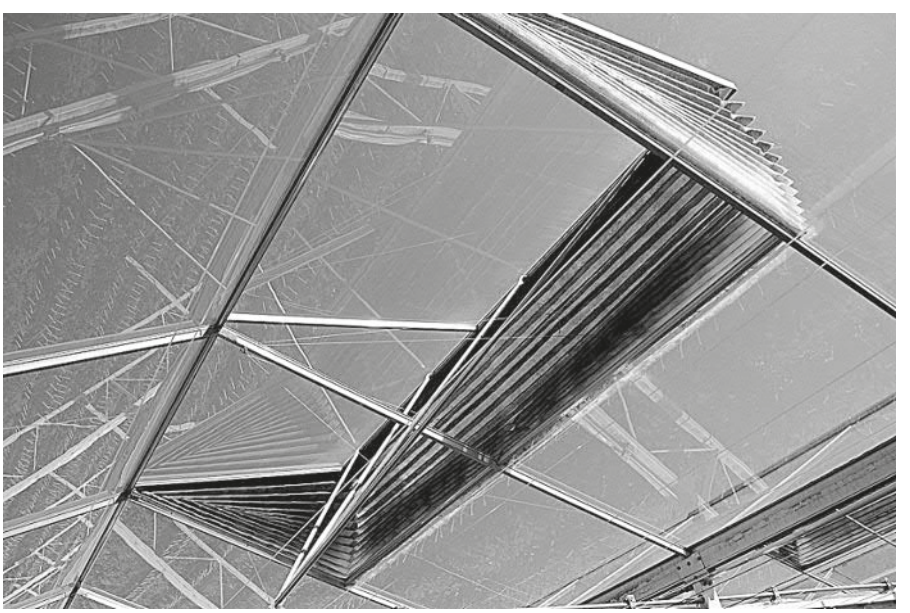

FIGURE 12.12 Roof vent with insect screen. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 12.13 Four acres of solar photovoltaic system with water-retention pond below. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 12.14 Tilting solar panels above electrical panels. (From Houweling's Group, Camarillo, CA. With permission.)

older greenhouse ranges burn natural gas to create carbon dioxide to enrich the atmosphere during the day. The heated water from the boilers generating the CO_2 is stored in these large storage tanks. This heated water is pumped back through the boilers to heat the greenhouse at night. Automated insulation screens close over the plants at night to hold in accumulated heat.

FIGURE 12.15 Powder coated structural membranes to improve light. Note: The height of the structure at the gutters is well above the crop. (From Houweling's Group, Camarillo, CA. With permission.)

The greenhouse metal structural membranes are powder coated to maximize light reflection to the crop (Figure 12.15). Below, a white weed mat on top of the floor also helps to reflect light up into the crop. With positive pressure and the high gutters, only a small number of roof vents are required. Each is covered by an accordion-shaped insect screen to maximize the surface area (Figure 12.12). The vents are needed only to release pressure in the greenhouse so that excess pressure does not break the glass. All this is controlled by the Argus computer system. The atmosphere in the greenhouse is constantly recirculated by the use of horizontal airflow fans and the large polyethylene convection tube located under the raised growing trays (Figures 12.10 and 12.11). At the greenhouse wall on the outside is an insect screen to prevent insects from entering as the exhaust fans take in the outside air (Figure 12.5). An evaporative cooling pad located on the same outside wall permits air from outside to be drawn through it to reduce temperature by evaporation of the water running down the cooling pad (Figure 12.6). From there, the cooled air is pushed down the convection tubes under the plants by two exhaust fans per plant row.

Temperature control is by glass shutters that adjust to any degree to permit air from outside to mix with the inside greenhouse air. During heating cycles, the cooling pads are covered with this shutter in its closed position and the air from the fans is pushed through heat exchangers (Figure 12.7). There are two heat exchangers per set of two fans per plant row. The heat exchangers use hot water from the storage tanks and boilers of the other greenhouse ranges. When no or little cooling is required, the louver system partially closes to the degree needed to just mix the correct amount of cool air with the recirculated air. This is all controlled with the Argus computer system. There are heating pipes in the aisles between the plant rows, but they are not connected to the hot water heat. Their only purpose is to act as tracks for the picking/working carts to travel on. After the hot water passes through this new positive-pressure greenhouse, it goes back to the main boilers of the other greenhouse ranges and is stored in the large water tanks (Figure 12.4). The new range has no boilers; it only uses the residual hot water from the other ranges' boilers.

Another recent component in heating as part of the sustainable agriculture greenhouse technology is "combined heat and power" or CHP. This is also known as cogeneration that uses reciprocating

engines fueled by natural gas to generate electricity and produce heat and emits relatively clean carbon dioxide (Figure 12.16). Flue gases pass through a catalytic converter to remove any harmful components such as ethylene, then pass through a scrubbing unit and filter before injecting clean carbon dioxide into the greenhouse. The electricity is either sold to the grid when called upon or used in the operation of the greenhouse components and supplementary lighting. Any excess electricity can only be sold to a community grid if a Power Purchase Agreement (PPA) is in place.

Cold return water from the greenhouse and/or hot water storage tanks flows through the engine heat exchanger to pick up the heat generated by the engine thus cooling the engine jacket and the heated water is distributed by the hot water piping into the greenhouse to heat the greenhouse environment. If the heat is not needed in the greenhouse at a particular time, the heated water can be directed to a large hot-water storage tank as discussed above.

Other cogeneration sources of heat include geothermal and waste heat from operations such as power stations. This involves using hot water from either geothermal sites, such as done in many greenhouses in Hokkaido, Japan, Turkey, and locations in North America or from heated water from cooling towers in the generation of electricity. The most successful large greenhouse operations are from waste heat of industries that require large volumes of water in their cooling. A successful operation of this nature is Houweling's Group in Mona, Utah. They constructed a 28-acre (11 ha) phase 1 of Ultra-Clima greenhouse in 2014 (Figure 12.17). In 2021 Houweling's Group in Mona, Utah have begun a 30-acre (12 ha) expansion to begin production in 2022.

Their objective is to expand over 4 phases to 113 acres (46 ha) as demand for their products grow. This cogeneration project is with PacifiCorp Energy who is the owner/operator of the Currant Creek Power Plant and Rocky Mountain Power who supply the electricity to the national energy grid. The greenhouse uses waste CO_2 and heat from the generators stacks of the natural gas fired electrical generation facility (Figures 12.18 and 12.19).

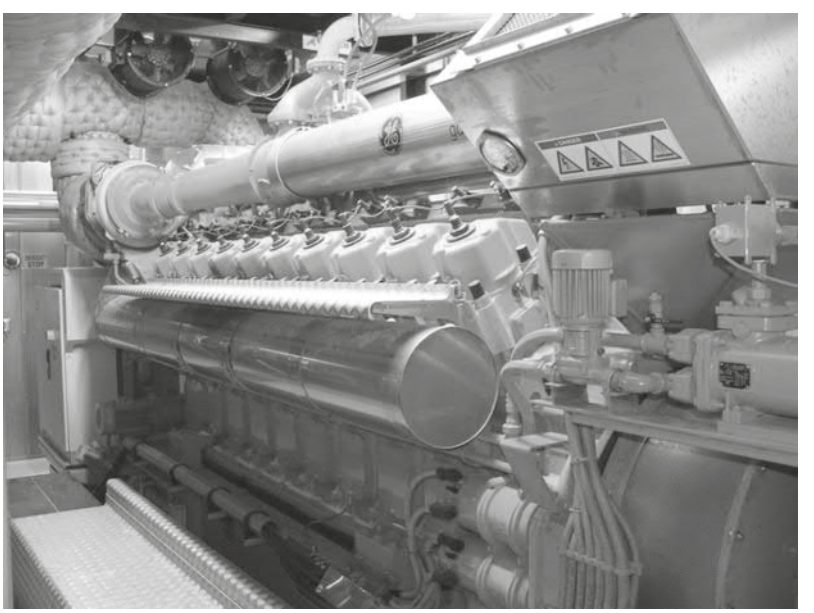

FIGURE 12.16 Combined heat and power unit. (From Great Northern Hydroponics, Kingsville, ON., Canada. With permission.)

FIGURE 12.17 Houweling's Group cogeneration greenhouse of 28 acres (11 ha) using waste heat from power plant. (From Houweling's Group, Mona, UT. With permission.)

12.2.3 Unit (Space) Heaters

Unit heaters or space heaters are another method of heating greenhouses. These are self-contained heaters requiring natural gas or propane as their fuel. They have a fan attached to the back of the unit to blow air across heat exchangers producing hot air into the greenhouse. A fan-jet convection tube is mounted to the end wall of the greenhouse. The heater(s) mounted on the side of the fan-jet blow the hot air into the fan-jet that rapidly blows the heated air down the length of the greenhouse. Fan-jet and convection tubes come in 18-, 24-, and 30-inch (46-, 61-, and 76-cm) diameters. One fan-jet system for good air distribution is sufficient for a greenhouse width of 30 ft (9 m) (Figure 12.20). Houses from 30 to 60 ft (9 to 18 m) in width should use two fan-jet and tubes.

If a large amount of heat is needed in cold climates two unit heaters, one on each side of the fan-jet would blow heated air into the fan-jet system (Figures 12.20 and 12.21). The convection tube is perforated on the lower sides at the 4- and 8- o'clock positions to allow the heated air to blow down toward the crop. Each convection tube is punched to match the selected Fan-Jet volume and length of the tube. The system is mounted above the crop near the apex of the greenhouse structure. The unit heaters must be vented outside of the greenhouse to allow combustion gases to escape away from the greenhouse.

A unit heater is sized according to the BTU output needed to heat the volume of air to optimum temperatures. One or two unit heaters are mounted near the end wall of each bay (range) of the greenhouse. These are good for greenhouse ranges up to about 120–130 ft (36–40 m). If greenhouse ranges are longer, two fan-jet-heater systems may be used, one from each gable end of the greenhouse going to the middle of the house, for example, a 200 ft (61 m) long range would have two systems, each 100 ft (30 m) long. Manuals with tables are available to calculate the heating and cooling needs of a greenhouse with a specific climate to select the correct model of unit heater(s) and fan-jet systems (see Acme Engineering & Manufacturing Corp., (1979)).

FIGURE 12.18 Waste heat and CO_2 are ducted to the greenhouse from the natural gas power plant. (From Houweling's Group, Mona, UT. With permission.)

FIGURE 12.19 Ducting of waste heat and CO_2 to the greenhouse from the natural gas power plant. (From Houweling's Group, Mona, UT. With permission.)

12.2.4 Ventilation and Cooling

The fan-jet also serves for cooling and introduction of fresh air into the greenhouse by thermostatically controlled motorized shutters (louvers) that remain closed during heating, but open if cooling or introduction of fresh air is required (Figure 12.21). In addition to a fan-jet system is

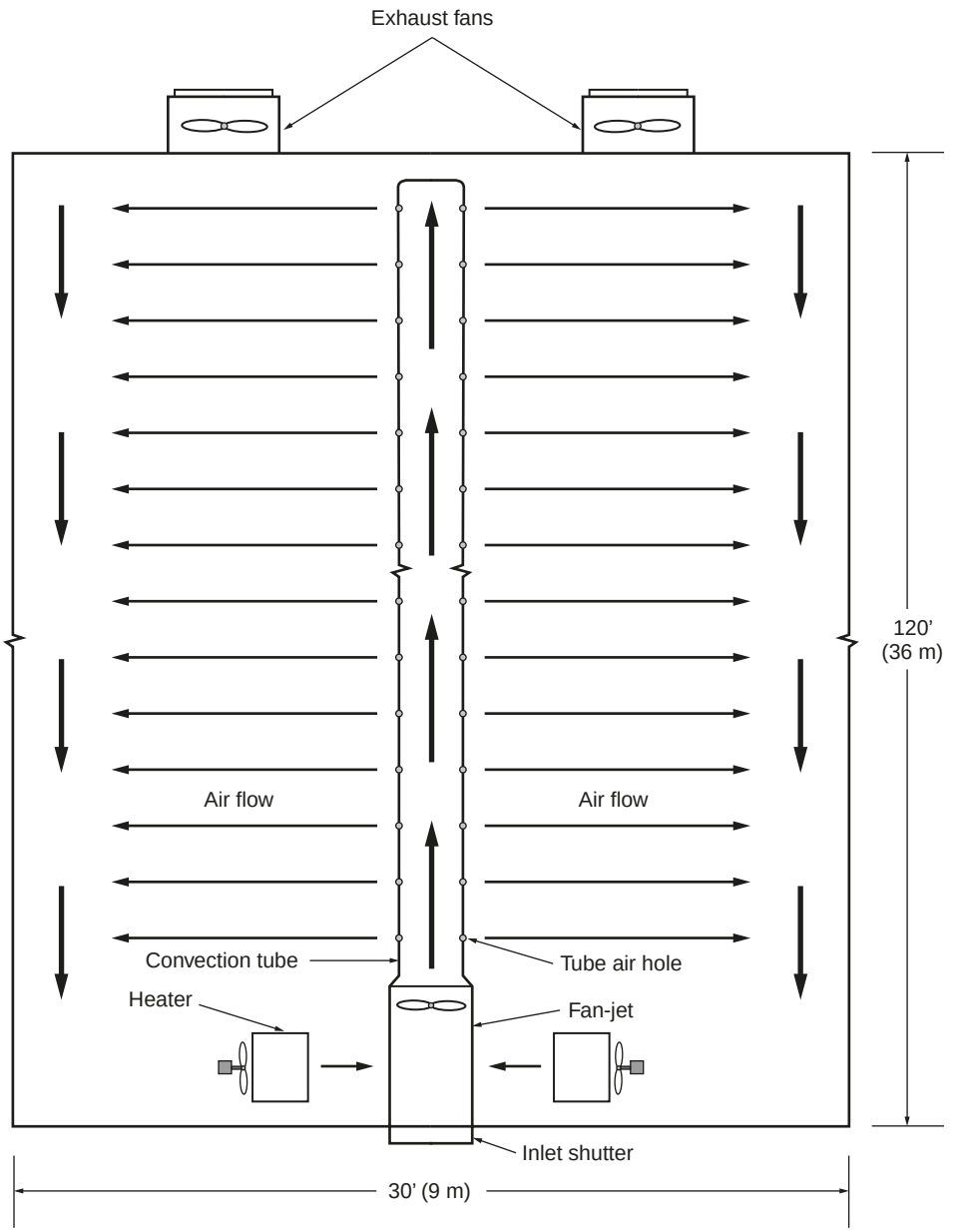

FIGURE 12.20 Layout of Fan-Jet with convection tube and unit heaters. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

installation of horizontal air-flow (HAF) fans that circulate the air of the greenhouse (Figure 12.22). Refer to Sparks (2018) for information on greenhouse air flow. The HAF fans are placed within the greenhouse above the crop, but, below any energy curtain to permit air circulation during the night and day. The air circulation throughout the crop keeps air temperatures uniform, reduces humidity, improves air flow within the crop, and improves CO_2 distribution within the plant canopy. Their spacing and arrangement for a typical range is given in Figure 12.23. The fans come in various sizes that determine the volume of air movement. They vary from 12- to 24-inch diameter fans. The number

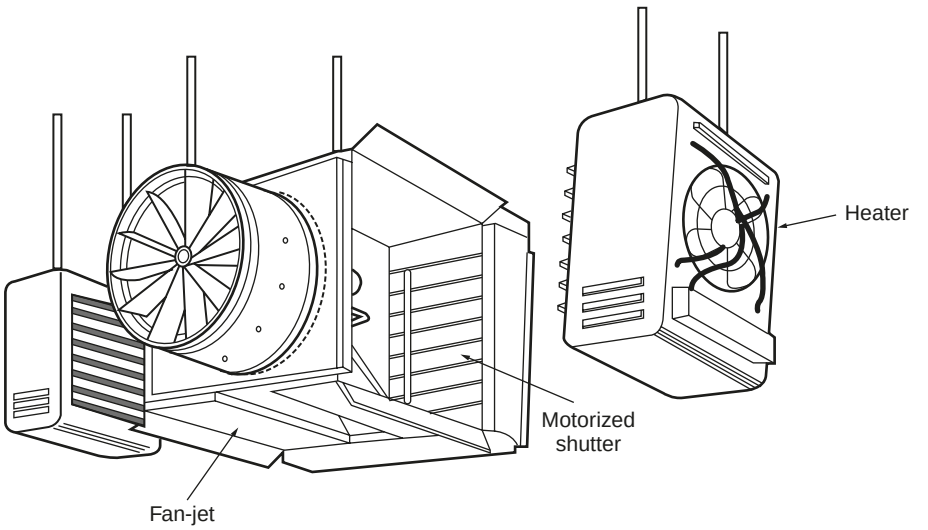

FIGURE 12.21 Fan-Jet with unit heaters. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 12.22 HAF fans for air circulation.

and spacing depends on the fan size and dimensions of the greenhouse. As shown in Figure 12.23 with all houses these fans are located in two rows per range and oriented in opposing directions. The first fan should be located about 10–15 ft (3–4.5 m) from the end wall and the others about every 40–50 ft (12–15 m) apart. They should be positioned so that they are capable of moving the air at 50–100 ft (15–30 m) per minute.

Bartok, J. and Grubinger, V. (2019) suggest that the total fan capacity should be equal to two times the floor area. For example, for a 30 ft x 140 ft (9 m x 42.6 m) greenhouse range (Figure 12.23): 30 x 140 x 2 = 8,400 cfm total movement of air is required. The number of 12-in. fans needed would

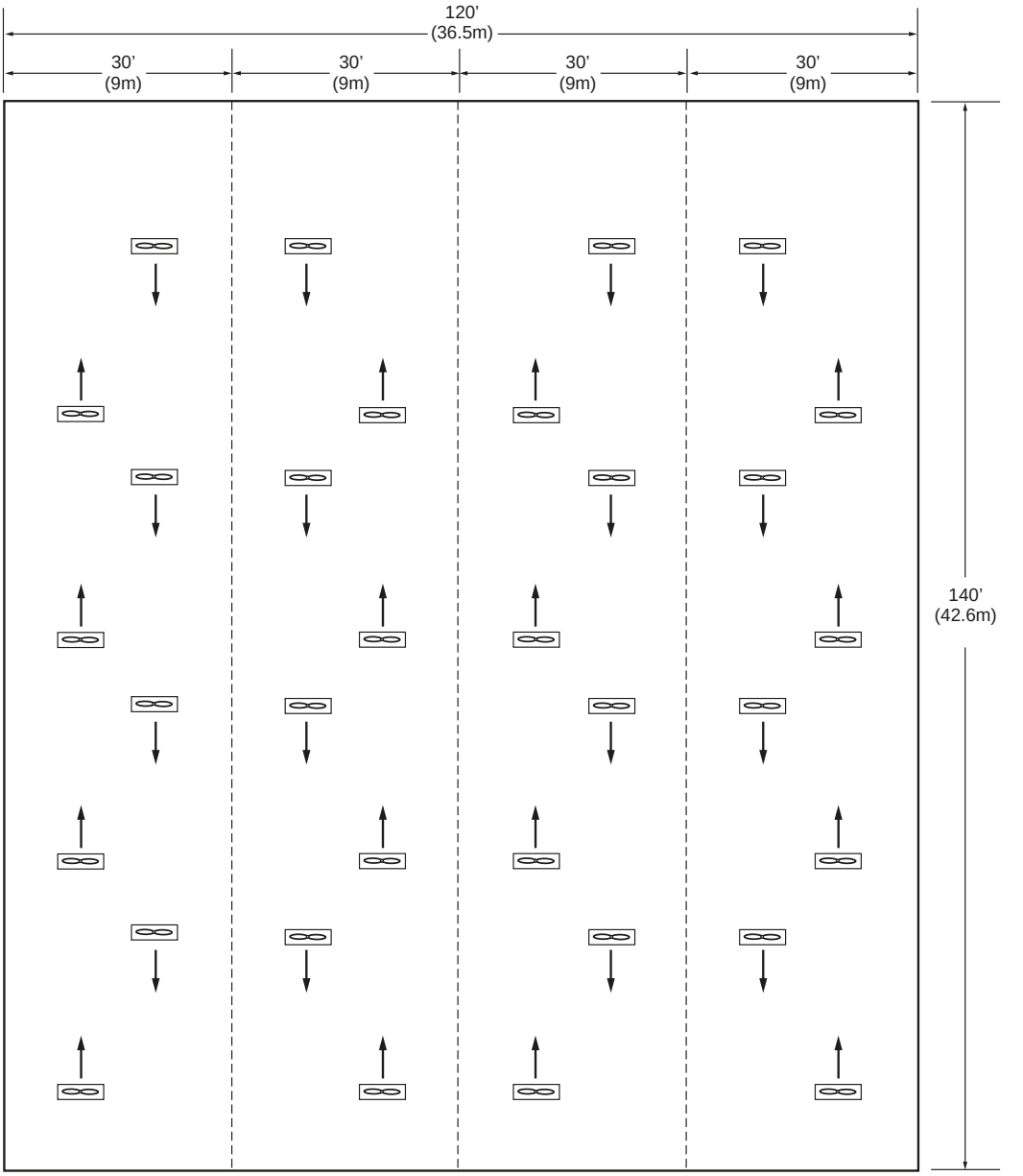

FIGURE 12.23 HAF fan layout in greenhouse with four ranges. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

be: 8,400/1,020 = 8 fans. They recommend operating the HAF fans 24 h per day when the exhaust fans or vents are closed, but should automatically stop via a relay when the exhaust fans and/or vents are open.

Most greenhouses now use ridge vents for cooling by natural ventilation. This is particularly true of gable roof glass houses, but even some polyethylene structures have the option of roof vents. The ridge vents may run the entire length of the house as single or double roof vents on either side of the ridge. This cooling-ventilation system may also use side wall vents. The use of side vents only may not be as effective as they depend on wind movement through the greenhouse. John Worley

(2014) states that ridge vents should be about one-fourth the greenhouse floor area with side vents of the same area. As discussed above with Ultra-Clima systems of positive pressure the ridge vents are reduced in area by 90 percent.

Natural ventilation is achieved through thermal gradients, creating circulation of the air as heated air rises. If exhaust fans are used to force air through the greenhouse the roof and side wall vents must automatically close when the exhaust fans are operating. If not, the fans will short-circuit movement of air through the vents rather than through an evaporative cooling pad. A brief description of a pad-fan cooling system is presented here; however, for details on design there are many good publications listed in the References section of this chapter. The Ultra-Clima system of using an evaporative cooling pad and distribution fans within an environmental control chamber was discussed earlier.

Exhaust fans may be placed in the greenhouse end walls or in a side wall opposite to the end having the evaporative cooling pad (Figure 12.24). For best results, the house should not exceed 130 ft (40 m) in length or width if pulling air across a number of ranges in a gutter connected greenhouse. It is very important to note that in areas of high solar energy combined with high RH; this evaporative cooling system is not very efficient and almost nonfunctional with ambient RH of 80% or greater as the water running over the cooling pad does not evaporate and therefore without the evaporation process cannot remove energy from the air. For best results the exhaust fans should be sized to be capable of exchanging the entire greenhouse air volume twice per minute. Without a cooling pad this rate of air exchange should keep a temperature rise within the greenhouse of 5°F (3°C). The greenhouse must be sealed from the outside so that no leakage of air moves through any openings. Exhaust fans come in various diameters and motor sizes.

They are also available with single or two speed motors. The size is determined by the maximum ambient temperatures, volume of the greenhouse and type of greenhouse structure. All can be calculated from numerous manuals listed in the References section.

When the exhaust fans are operating with an evaporative cooling pad all ridge vents, if any, and the louvres of a fan-jet system must automatically close to force all air through the cooling pad. To

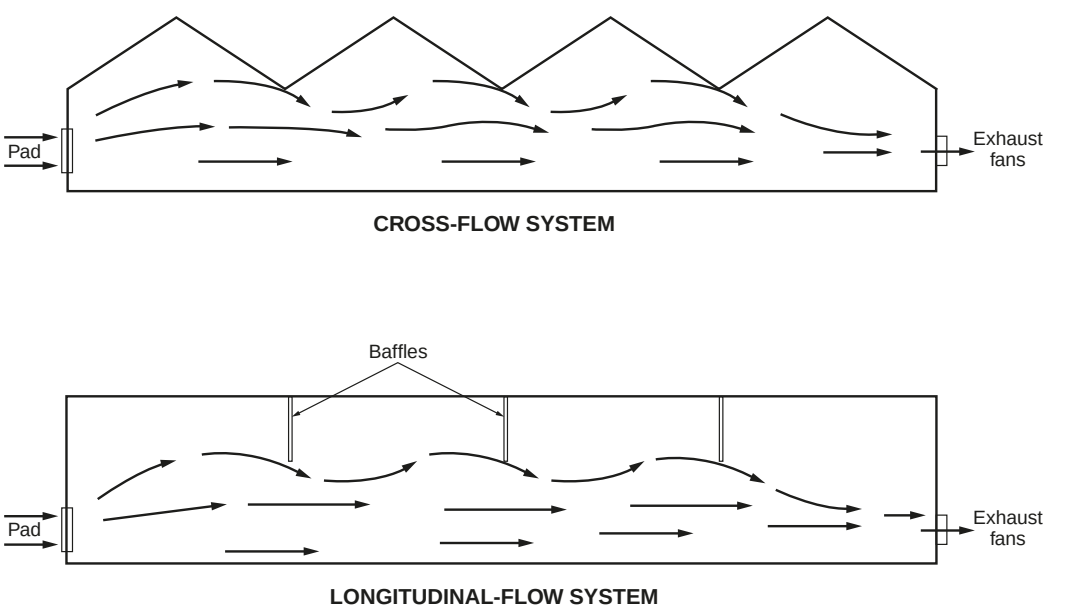

FIGURE 12.24 Cross-flow and longitudinal-flow air movement systems. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

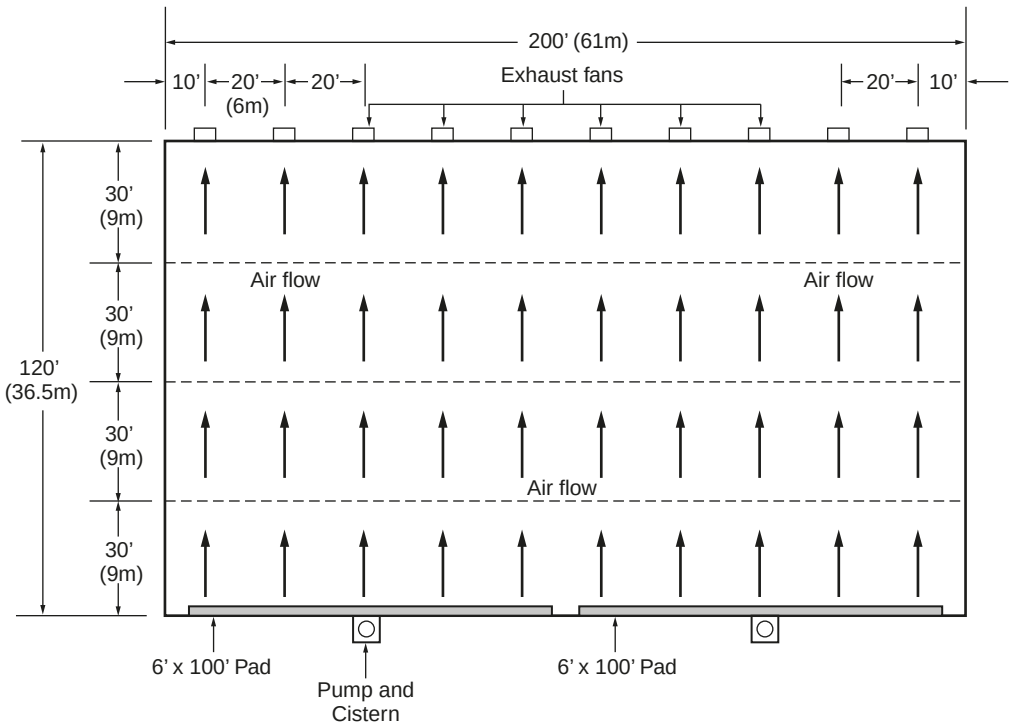

FIGURE 12.25 Layout of pad-fan cooling system. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

achieve cooling within the greenhouse an evaporative cooling pad is needed through which the fans move air into the greenhouse (Figure 12.25). The dimensions and thickness must be calculated by referring to manuals on cooling systems. The area of the cooling pad also depends on the cooling pad material. Most cooling pads use corrugated cellulose in thickness of 4 in. (10 cm) and 6 in. (15 cm).

A typical evaporative cooling pad with water reservoir, pump, pipe distribution, and collection pipe or tray is shown in Figures 12.26 and 12.27 and referred to by Bucklin et al. (2013). A pump circulates water over the cooling pad and the water percolates through the pad to be collected at the bottom in a return pipe or channel, where it flows back to the water reservoir. There are two phases typically: the first is the exhaust fans turn on at lower speed (if two-speed fans) and air is moved through the dry cooling pad as the pad vent opens. As temperatures exceed a second pre-set level the exhaust fans increase their velocity to the second speed and the cooling pad pump is activated to moisten the pad. An insect screen on the outside of the cooling pad prevents insects from entering. Motorized vents close the cooling pad when cooling is unnecessary and when the heating system is operating.

As water moves through the cooling pad and evaporates it removes about 8,100 BTUs of heat from the air as each U.S. gal of the water changes from liquid to vapor. As the air moves across the greenhouse it picks up heat from the plants and solar radiation causing a temperature gradient between the cooling pad and exhaust fans. This gradient can be as much as 15°F (8°C) or greater depending on the crop density, greenhouse gutter height, and greenhouse roof configuration. The design of the cooling system may be longitudinally from one end to the other of the greenhouse or across the greenhouse ranges as shown in Figure 12.24. In a cross-flow system the gutter height of the greenhouse will act as baffles forcing the air flow through the crop. In a longitudinal flow system

FIGURE 12.26 Evaporative cooling pad with return pipe below and reservoir to right. Note: The side vents are partly open as the pad is not operating.

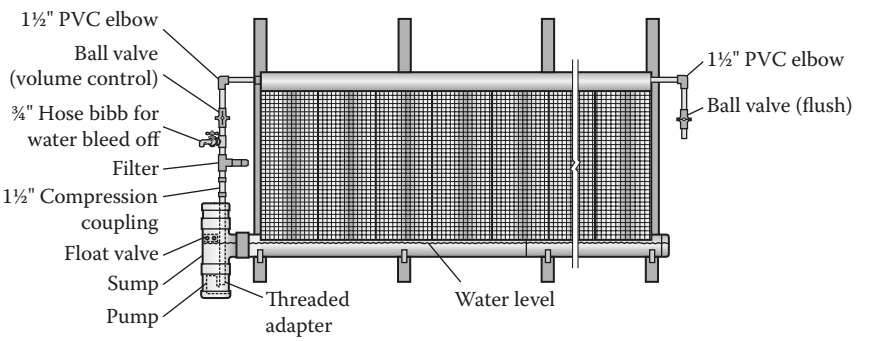

FIGURE 12.27 Evaporative cooling system. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

transparent baffles just above the crop could be used or a shade curtain system may be drawn to assist in directing the air movement downward.

Alternatively to an evaporative cooling pad system is to use misters. This is an expensive system requiring many mist nozzles on lines located above the crop. It requires very high pressure and clean water. As a result, a very effective filtration system to remove any particles in the water is important or the mist nozzles will clog and wear. Water is pressurized to 1,000 psi (70 bars) and distributed through nozzles that produce water droplets of 10 microns in diameter. Uniform distribution throughout the greenhouse produces uniform reduction in air temperatures. Of course, similar to evaporative cooling pads, the efficiency of cooling is dependent on the relative humidity of the ambient air and the movement of air through the greenhouse by use of exhaust fans. Such fogging systems may be used in greenhouses having only natural ventilation through ridge vents. To design the fogging system the position of the vents and/or exhaust fans are important factors in optimizing the fogging system.

Shade and thermal curtains are a standard method of reducing light from entering the crop and heat from escaping at night. The curtains are located above the crop under the greenhouse gutters (Figures 12.28 and 12.29). This curtain system is mechanical, operated by the central computer

FIGURE 12.28 Single shade screen system. (From Prins Greenhouses, Abbotsford, BC, Canada. With permission.)

FIGURE 12.29 Double shade screen system. (From Prins Greenhouses, Abbotsford, BC, Canada. With permission.)

monitoring light and temperatures in the greenhouse. The curtains are supported by cables and their movement across the cables operated by a motor.

The shade curtains are available in a number of different percentages of light penetration and thermal curtains in percentages of heat retention. Growers claim up to about 50% energy savings compared to having no curtains. The lower curtain is the energy curtain that provides from 25% to 35% savings in heat loss and the upper is the shade curtain that regulates the amount of sunlight entering the greenhouse, but, also saves about 15% to 20% in energy use. Svensson (www.ludvigsvensson.com) is one company that manufacturers shade and thermal curtains specifically for greenhouses. The choice of shade and thermal curtains vary with the crop and ambient weather conditions. Shade curtains focus on percentages of light diffusion, solar control, and some energy saving. Thermal curtains emphasize energy savings and light diffusion. For example, shade curtain percentages vary from 13% shading and 15% energy saving to 86% shade combined with 45% energy saving and many other percentage combinations for other types of shade curtains. Whereas thermal curtains vary from a combination of 11% shade with 45% energy saving to 29% shade with 45% energy savings. These are only a few of the combinations of shade, solar diffusion, and energy savings available from numerous types of curtains by Svensson. The grower must work closely with the manufacturer in determining the best combination of curtains to use for their crop and environmental conditions. Shade and thermal curtains may also be installed vertically to reduce light levels entering the side walls and reduce energy loss during the night or cold periods of dark weather (Figure 12.3).

An older, simpler, but labor-intensive method of shading is the use of a shade compound sprayed on the roof of the greenhouse. For large commercial operations this task can be applied by a roof washer machine that travels in the gutters. The machine cleans the roof and gutters. Large greenhouses must clean their roofs continuously, usually at night, using this machine (Figure 10.36). If a greenhouse is located in a dusty area like a desert, cleaning the roof must be done daily to avoid loss of light transmission.

By attaching special spray beams to the roof washer it transforms the machine into a shade (chalk) application machine. "ReduHeat" is a typical shade compound that would be applied in March–April and should wear off from rainfall by September to October when ambient light and heat have subsided. "ReduSol" is a shade removing compound that can be used if the shade compound does not wash off from normal precipitation.

12.3 CARBON DIOXIDE (CO_2) ENRICHMENT

Many studies have been done over the past 50 years on the benefits to greenhouse crops by increasing the levels of CO_2 in greenhouses. All these crops benefit from CO_2 enrichment increasing yields, shortening cropping cycles, and producing healthy plants. The ideal concentration depends on the crop, crop growth stage, light intensity, and temperature. The increase in production is generally 20% or higher compared to growing crops without CO_2 enrichment. The optimum levels of CO_2 enrichment vary with different crops. Normal enrichment levels vary from 800 ppm in the case of many vine crops to 1,100–1,200 ppm for leafy greens and lettuce. For most crops the saturation point is reached at 1,000–1,200 ppm, higher levels than that are not beneficial (Figure 12.30). Normal ambient CO_2 levels vary from 350 to 400 ppm depending on the location. Near cities the levels of CO_2 may be higher. CO_2 enrichment is applied only during daylight at which time photosynthesis is taking place. During the night with dark respiration CO_2 is released by the plants. These levels drop rapidly at sunrise as photosynthesis substitutes for respiration.

There exists a significant relationship among CO_2, light levels, and rate of photosynthesis. This is especially important during low light levels of winter months, whereby CO_2 enrichment can compensate for low light levels and result in higher rates of photosynthesis at a given light level. Ventilation with resultant air movement within the crop canopy also determines the effectiveness of

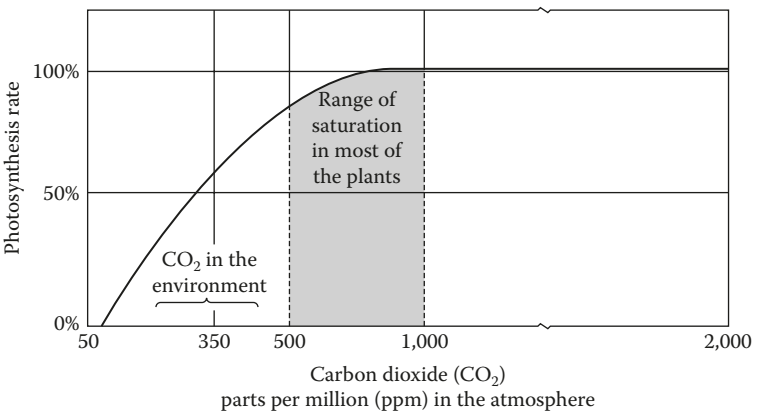

FIGURE 12.30 Graph of photosynthesis activity versus carbon dioxide (CO_2). (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

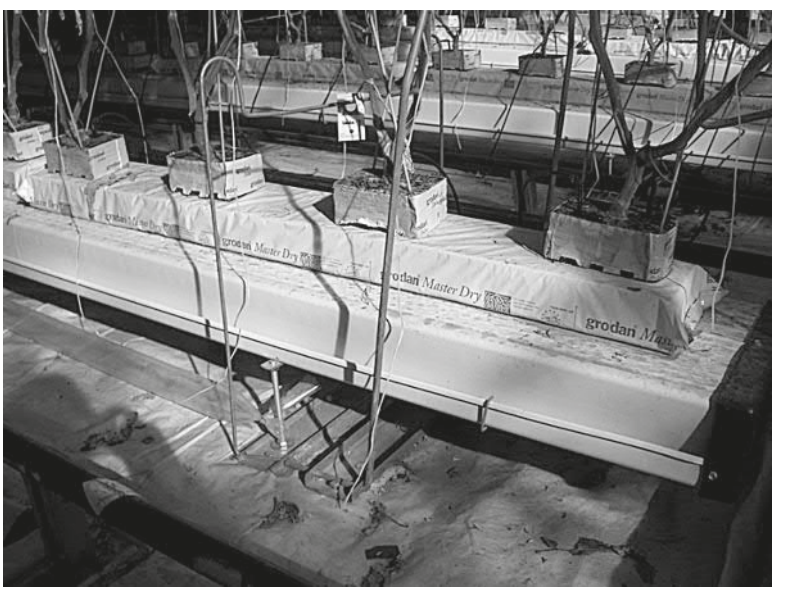

FIGURE 12.31 CO_2 tube located on floor below raised tray. (From Eurofresh Farms, Wilcox, AZ. With permission.)

CO_2 exchange across the leaf air boundary layer. For the CO_2 to enter the leaf stomatal openings, it must be in close proximity to them. Diffusion into the leaf is greatest with high concentrations of CO_2 outside the leaf compared to levels inside the leaf. In greenhouses CO_2 is applied in small tubes located at the base of the plants so that it can rise up into the crop canopy (Figures 9.3, 9.6, and 12.31). With the raised tray method of growing vine crops the CO_2 tube is located below or to the side of the raised troughs. The CO_2 naturally rises through the crop to the top of the greenhouse.

Carbon dioxide is generated by injecting compressed bottled CO_2, CO_2 burner units located above the crop and the preferable system by using flue combustion gases from a central boiler or CHP unit. Any fired units must use a clean source of natural gas or propane that combusts close to 100% of the fuel leaving byproducts of CO_2, other gases as ethylene, which must be removed by a

CO_2 recovery unit, and water that is discharged. CO_2 burner generators are located throughout the greenhouse above the crop. With these units mixing of the air volume within the crop canopy is critical to efficient uptake. HAF fans can assist in obtaining relatively homogenous mixing of the CO_2 with the greenhouse air. These generators do produce heat that may be an advantage during cold temperatures, but a disadvantage during hot weather. During hot, sunny weather it would be advantageous to have a highly efficient ventilation and cooling system to bring in fresh ambient air that contains about 350 ppm of CO_2 and at that time not operate the CO_2 generators. Research over the years has proven that levels of CO_2 below 340 ppm (ambient level) within the greenhouse atmosphere negatively affect plant growth and productivity. If a greenhouse is small or uses a boiler fired by other sources than natural gas or propane, bottled liquid CO_2 is a good alternative. The liquid CO_2 is very pure with no heat or moisture production. Large tanks are available that can be filled by a bulk delivery truck (Figure 12.32). The liquid CO_2 is distributed within the crop by use of black flexible tubing with holes punched along its length. Large greenhouse operations using natural gas fired boilers for heating take flue gas from the boiler to enrich the crop with CO_2. They use a flue gas condenser connected to the stack just above the boiler (Figure 12.33). All impurities such as ethylene and other gases, as well as water from the flue gas, must be removed by passing it through a scrubber and filters. From there the CO_2 is blown through large distribution pipes to the greenhouse side wall perpendicular to the crop rows. From these distribution pipes are attached header pipes that then connect to clear polyethylene tubes (2.5-in. or 6.5-cm diameter) located at the side of the plant rows or underneath the raised trays (Figures 9.6 and 12.31) if that growing system is installed. In the Ultra-Clima (positive pressure convection tube) system CO_2 travels in piping with risers connected to the ventilator fans that force air via the convection tubes under raised troughs supporting the crop (Figures 10.35, 12.9 through 12.11).

The key to successful CO_2 enrichment for efficient use is to achieve uniform distribution within the crop canopy by good ventilation and air movement through use of HAF fans and fan-jet systems.

FIGURE 12.32 Large tank of liquid CO_2. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 12.33 Natural gas fired boiler with CO_2 recovery unit. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 12.34 Water storage tanks (silos). (From Flavorite, Warragul, Victoria, Australia. With permission.)

12.4 RELATIVE HUMIDITY (RH)

Humidity is the amount of water vapor present in the air. Relative humidity (RH) is the amount of humidity present as a percentage of the maximum possible at a given temperature. Saturation is 100% RH and dry air with no water vapor is 0% RH. There is an inverse relationship between temperature and RH. As the temperature increases, RH falls and vice versa. Warm air can hold more

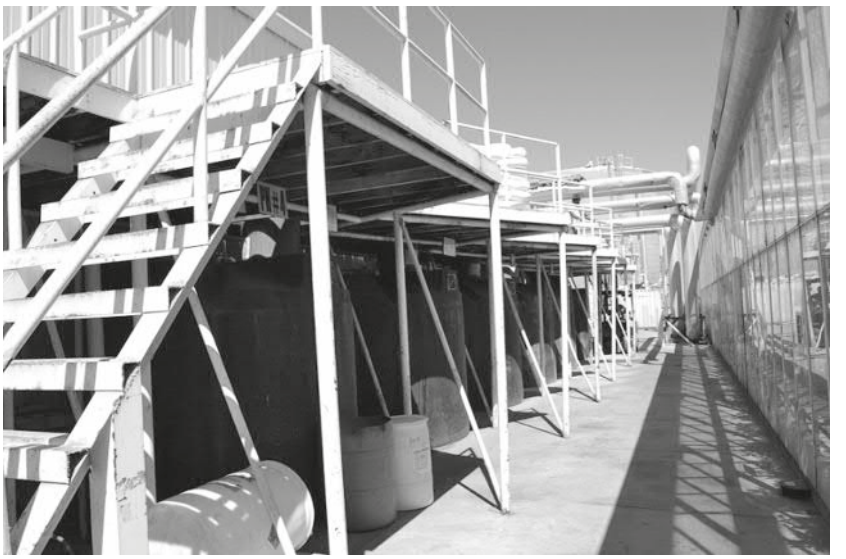

FIGURE 12.35 Stock tanks of 3,000 gal. (From Houweling's Group, Camarillo, CA. With permission.)

water vapor than cool air. The RH falls as air temperature rises if no moisture is added to the air. The dew point is the air temperature at which the air reaches saturation and condensation will occur. This must be avoided in a greenhouse, as condensation would form on plant leaves making them vulnerable to disease infection. Increasing the air temperature by 10°C (18°F) about halves the RH, therefore almost doubles the water holding capacity.

To lower the RH in a greenhouse during cool, damp days the greenhouse temperature may be raised and new air brought into the greenhouse to exchange the air. This is achieved by fan-jets, exhaust fans, and cooling pad louvers. Fan jet louvers can open and ambient air, even if at 100% RH, can be drawn into the greenhouse passing through the heated air of unit heaters and conducted down the fan-jet convection tube. As the air is heated the RH falls, so this introduced heated air can then be distributed through the crop with assistance of HAF fans. The introduction of outside air into the greenhouse creates positive pressure that will force air out of the greenhouse through exhaust fan louvers or sidewall vents (cooling pad vents). The cooling pad vents would open slightly according to preset levels for RH control to permit the volume of air entering to exit.

With an Ultra-Clima (positive pressure) system, pad vents could be opened to permit outside air to enter the greenhouse through the environmental chamber. It would pass through the heat exchangers using hot water heating and raise the air temperature to optimum levels for the crop before it enters the ventilators to be forced down the poly convection tubes that are located under the raised tray beds with the crops. The positive pressure within the greenhouse would then expel air through the roof vents. The new air, as it is heated, its RH is lowered and on mixing with the higher RH air of the greenhouse, reduces the overall RH of the greenhouse air.

RH is measured as vapor pressure deficit (VPD). Broad (2008) explained clearly the relationship between RH and VPD. VPD measures how much the air is below saturation at a given temperature. It signifies the shortage (deficit) of moisture in the air. There is a maximum vapor pressure for any given temperature, which is the saturation pressure (100% RH). The VPD is the difference between the actual vapor pressure at a given temperature and the maximum (saturation) vapor pressure. VPD goes in the direction opposite to RH. When RH is high, VPD is low. If the VPD is very high plants

become hard, with slow, generative growth. If the VPD is too low the crop will become very vegetative with soft, weak growth predisposing the plants to disease infection.

Atmospheric pressure is typically 14.7 psi or 101kPa. This is the pressure exerted in the atmosphere by all gases and water vapor. VPD is measured in kilo Pascals (kPa). One kPa is 1,000 Pa. The following are some conversions of other pressure measurements to kPa.

1 bar = 1 atmosphere (atm) 1 bar = 100 kPa 1 psi = 6.895 kPa

An example of VPD in a greenhouse under hot, dry conditions VPD = 1.25 kPa; cool, damp conditions VPD = 0.45 kPa; and more ideal conditions VPD = 0.85 kPa. Of course, the optimum ranges depend on the crop, stage of growth and steering of vegetative versus generative phases in fruit crops. VPD indicates if plant stress is caused by either excessive transpiration (high VPD) or lack of adequate transpiration due to low VPD. Under high RH (low VPD) plants are unable to evaporate sufficient water to enable adequate mineral uptake. For example, tip burn occurs in lettuce growing under high RH (low VPD) as inadequate calcium is taken up by the plant. There may be optimum levels of calcium in the nutrient solution, but the plant is not transpiring sufficiently to take up the water and minerals. Splitting and cracking may occur in tomatoes as the plants are unable to evaporate sufficient water and tugor pressure builds up in the cells. When VPD is too high (low RH) evapotranspiration in the leaves may exceed water uptake by the plant roots. Plants will wilt and stomata will close preventing CO_2 exchange with a consequent reduction in photosynthesis.

12.5 IRRIGATION (FERTIGATION)

Many large greenhouses have 3 to 4 wells to extract ground water. During irrigation cycles the volume of water drawn from the well(s) may exceed their capacity in a given time, so to overcome shortages, the wells may operate day and night to pump raw water into large storage tanks termed water silos (Figure 12.34). With the water silos continuously filling from the wells there is a water buffer large enough to irrigate the crop for at least a day or more. Any greenhouses collecting rainwater runoff from the greenhouse roofs is also stored in water silos for later use in irrigation.

The time between irrigation cycles depends on a number of factors, including the type of growing medium used. Frequency and duration of irrigation cycles depends largely on the substrate water retention characteristics. Rockwool needs less irrigation than perlite. Refer to Chapter 10 on rockwool culture for specific details. Coco coir irrigation cycles are more similar to a peat-lite substrate as was described in Chapter 11. More frequent irrigation is needed after transplanting until the plants become established in the substrate. After that, 5 to 10 irrigation cycles per day may be adequate depending on environmental conditions and plant stage of growth. Perlite generally needs more frequent irrigation cycles than rockwool as it has less water retention.

Regardless of the hydroponic growing system (rockwool, sawdust, perlite, peat-lite, coco coir) a drip irrigation system with a fertilizer injector is used to provide the plants with water and nutrients. Refer to Chapters 9 and 10 for further details. Most hydroponic greenhouses use fertilizer injectors with stock solutions. Commercial greenhouse operations of 20 acres (8 ha) or greater may use a series of 3,000-gal tanks. Houweling's Group, Camarillo, California, located a series of stock tanks of about 3,000 gal outside under a platform between the greenhouses. The platform is of heavy steel-reinforced construction so that the fertilizers can be set above the tanks. Fertilizers can be added from above directly into the tanks (Figure 12.35). A plastic barrel with the ends removed is fixed to the manhole of each tank so that the fertilizers can be added with a minimum of spillage. These are stock solutions prepared for injection into the irrigation system on its way to the greenhouses.

In the past two-part stock solutions A and B in separate storage tanks use concentrated nutrient formulations of from 100–200 times normal strength. In addition, a stock solution of acid or base in the third tank adjusts the *p*H of the final solution. This type of injector design was presented in Chapter 3 and Figures 3.2 and 3.3. Presently, more growers are setting up the stock solutions separately for each fertilizer salt for the macroelements and a separate one for minor elements as shown in Figure 3.4. The reason for this is versatility in adjustment of the nutrient formulation. These adjustments are made during changes in sunlight conditions and enables flexibility in steering the plants. The injector dilutes these concentrates proportionally with water in a blending or mixing tank or in large main lines as the solution is pumped through the drip irrigation system.

Recirculation systems are part of the sustainable yields program to conserve water and efficiently utilize the use of fertilizer salts. New systems utilize computer feedback systems that monitor and adjust the return solution from the crop. Refer to Chapter 10, Section 10.12.

Very large operations that re-circulate their nutrient solution through the collection of the runoff use vinyl-lined, corrugated steel tanks of 20,000 gal or more. Samples of the returned solution in the storage tanks are sent to a laboratory and results received within a few days. The nutrient solution is pasteurized at 85–90°C (185–194°F) for 3 to 2 min respectively, then cooled and adjusted for nutrients and *p*H by injecting stock solutions A and B on its way back to the greenhouses. If these greenhouses are located in southern latitudes where frost is not severe, such as California, the tanks can be located outside. In areas of cold winters, the tanks must be placed inside the greenhouse packing-storage building such as is the case with Bionatur Greenhouses in Jocotitlan, Mexico. The tanks are galvanized steel lined with vinyl (Figure 12.36).

In recirculation systems, the solution needs to be pasteurized before its return to the greenhouse irrigation system. This can be done by four methods: filtration, ultraviolet (UV), ozone, and pasteurization by heat. Most operations use filtration, UV, and heat pasteurization. Bionatur Greenhouses in Mexico and Eurofresh Farms (NatureSweet) in Arizona use filtration and UV as shown in Figures 12.37 and 12.38. Refer to Sections 10.9 and 10.12 of Chapter 10 for further information. These companies mainly grow tomatoes. They also use sophisticated injection systems as can be seen in Figure 12.37 to the left of the UV sterilizers and in Figures 12.39 and 12.40. The injectors

FIGURE 12.36 Large nutrient solution collection tanks in a closed system. (From Bionatur Invernaderos Biologicos De Mexico, S.A. De C.V., Jocotitlan, Mexico. With permission.)

FIGURE 12.37 UV sterilization system for recirculation of nutrient solution. (From Bionatur Invernaderos Biologicos De Mexico, S.A. De C.V., Jocotitlan, Mexico. With permission.)

FIGURE 12.38 Filters on the right with the UV on left. (From Eurofresh Farms, Wilcox, AZ. With permission.)

are controlled by the computer system. It monitors *p*H and EC and activates the injectors to adjust the returning nutrient solution.

In any recirculation system the raw water should be cleaned to remove any extraneous ions such as sodium (Na) and chloride (Cl). These ions are used by plants in small amounts and with the addition of raw water to the system a build-up will occur if they are present. As mentioned in Chapter 3 it is important to obtain a water analysis of all macro- and micro-nutrients in the raw

FIGURE 12.39 Fertilizer injector system. (From Bionatur Invernaderos Biologicos De Mexico, S.A. De C.V., Jocotitlan, Mexico. With permission.)

FIGURE 12.40 Large injector system. (From Bionatur Invernaderos Biologicos De Mexico, S.A. De C.V., Jocotitlan, Mexico. With permission.)

water to determine the treatment needed to reduce or eliminate them. Micro-elements that are often present in raw waters that may accumulate in a nutrient solution of a recycling system are iron (Fe), molybdenum (Mo), and boron (B). Usually a reverse osmosis (RO) treatment is part of the system to achieve the removal of extraneous ions.

Closed (recirculating systems) always run the risk of disease infection, so efficient disinfection must be part of the system. Disinfection is a combination of pasteurization, slow sand filtration (Biofiltration), UV radiation, and other methods.

Pasteurization is used mainly in vegetable crops and is effective against nematodes, fungi, bacteria, and viruses. In the process, the drain water is heated to 95–97°C (203–207°F) for 30 s. It is then pumped to a disinfected water tank and then diluted with new nutrient solution in a mixing tank.

Slow sand filters are used mainly in flowering and potted plants. UV radiation (Figure 12.37) can be used with slow sand filters (Figure 12.38). This filtration before passing through the UV sterilizer removes all color caused by organic compounds, making the UV treatment more effective. Injection of hydrogen peroxide (1 mmol/L) improves the efficiency of UV treatment (Runia and Boonstra, 2004). Extra iron has to be added downstream because of the degradation of iron chelates by UV. UV does not kill all pathogens or viruses.

The disinfection system is part of the overall irrigation-injection system as shown in Figure 12.41. Disinfected water makes up about 30% of the irrigation water. This disinfected water is stored in an opaque tank and from there is mixed with raw water and nutrients in the mixing tank before returning to the greenhouse irrigation system. In large greenhouses, enough nutrient solution is mixed for daily use and stored in a day stock tank. In this way, adjustments can be made in the formulation on a daily basis, depending on changes in weather, crop stage of growth, and growing balance between vegetative and generative phases.

Ozone purification (ozonation) is effective against bacteria, fungi, viruses, and any pathogens in the irrigation water and is more efficient than UV sterilization. Ozone consists of three atoms of

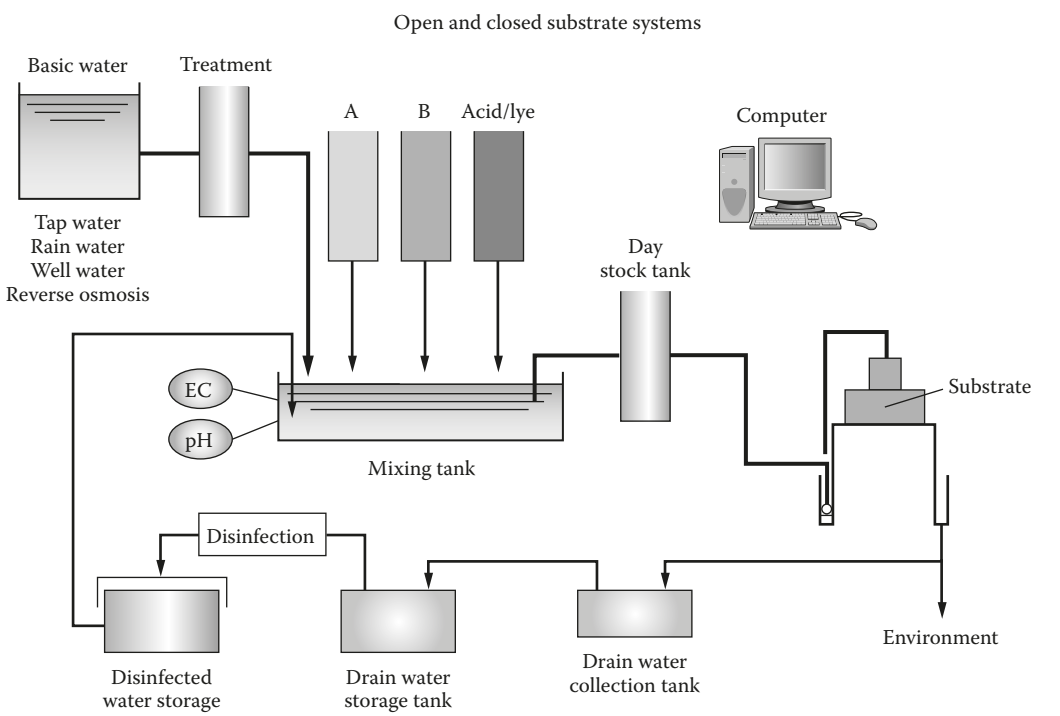

FIGURE 12.41 Overview of a complete disinfection-injection-irrigation system. (Adapted from K. Welleman, The Netherlands. 6th *curso y congreso Internacional de Hidroponia en mexico*. Toluca, Mexico, April 17–19, 2008. With permission. Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

oxygen (O_3), which oxidizes objects it contacts. It is supposed to be 99.99% effective in removing contaminants. It reverts back to oxygen within a short time. The use of ozone treatment has an added benefit to sterilization of water in that it provides dissolved oxygen in the irrigation water that benefits plant growth. The ozone generating equipment monitors water flow, EC, pH, and O_2 levels of the water with relays for control and alarms.

Fertigation systems are computerized with sensors within the greenhouse and crop. Moisture sensors measure the volume of water in the substrate relative to the volume of the substrate to give a percentage of moisture present. These sensors monitor the amount of water present in the plant root zone. The sensors relay information to the central computer to determine the irrigation cycles and duration. Changes in solar radiation, temperature, and RH all affect the water uptake by the plants. The grower sets threshold levels for the specific crop and its stage of growth and specifies the length of irrigation cycles. This conserves water, as the amount of leachate is maintained more constant. The grower can set the irrigation parameters to steer the crops from vegetative to generative phase or vice versa. The number of sensors within the crop needed to best represent the whole crop will have to be determined through experience with the crop.

Irrigation needs to meet the evapotranspiration rate of the plants, which in turn must be equal to the uptake of water from the rootzone. The stomata opening are related directly to water availability. If the stomates close due to lack of water, there will be a rise in leaf temperature as evaporation is not sufficient to keep the leaf temperature cooled. This relationship between leaf temperature and water uptake allows monitoring the need for irrigation by use of an infrared plant leaf temperature sensor. This information is sent to the central computer, which then may initiate irrigation cycles.

12.6 LIGHTING

During short days and low light levels of fall to early spring seasons greenhouse crops are not able to produce optimally due to lack of light energy. Supplementary lighting during these periods is highly beneficial to greenhouse crops. Most crops during this period of low light levels respond to added light at a rate of 1% increase in light to a 1% increase in yield, up to a point according to research by Marcelis et al. (2006).

Photosynthesis uses light visible to our eyes (Figure 12.42). The light is absorbed by chlorophyll, the green pigment, in all plant parts, especially in the leaves where most organelles called chloroplasts are located. The chloroplasts contain chlorophyll-a, chlorophyll-b, and carotenoid pigments. Most absorption of light is in the violet-blue and red light of the visible spectrum as shown by the absorption spectrum of these pigments (Figure 12.43). When we use supplementary lights for our plants indoors we want light that gives off most energy in this part of the visible light.

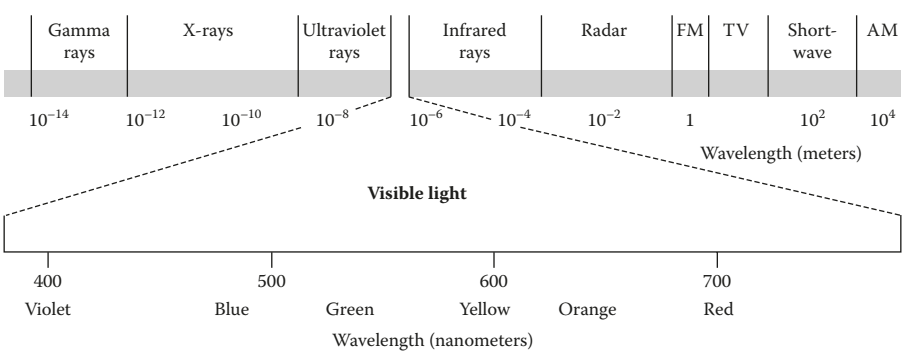

FIGURE 12.42 Visible light spectrum. (Drawing courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

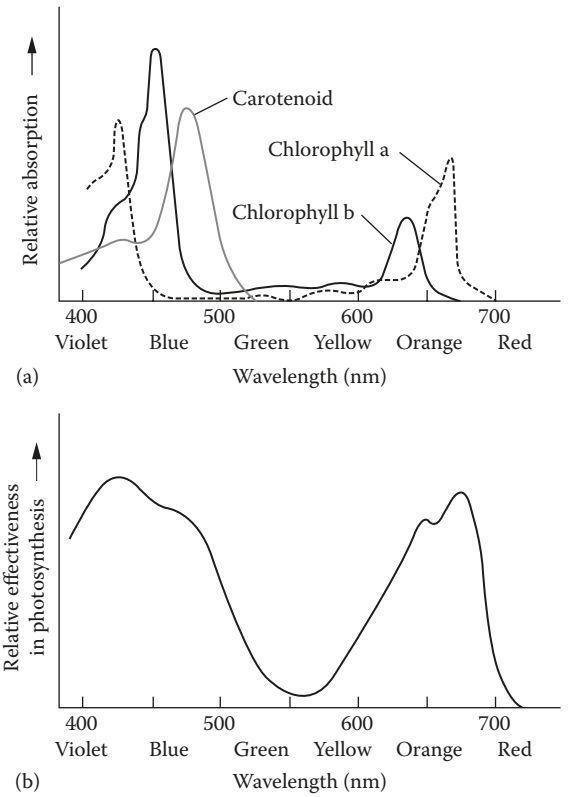

FIGURE 12.43 Visible light absorption spectra for chlorophyll and carotenoid plant pigments (A) and photosynthetically active radiation (PAR) in (B). (Drawing courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

During the day plants need the correct quality and intensity of light to drive photosynthesis. The quality refers to the color of light (determined by its wavelength). Plants want light between 400 to 700 nanometers (nm) wavelength, which is in the visible spectrum as shown in Figure 12.42. A nanometer is 10^{-9} or 1/1,000,000,000 meters (one billionth of a meter) in length. This light source that plants utilize is termed photosynthetically active radiation (PAR). This designates the solar radiation from 400 to 700 nm that plants actively utilize in photosynthesis (Figure 12.43).

Increasing light energy in the PAR range increases photosynthesis. Each crop has an optimum light intensity that maximizes plant growth. If there is insufficient light, plant growth slows and if excess light is given, plant growth will not increase (Figure 12.44). As a result, when using lights you must be sure to give sufficient, but not excess, as the cost of the additional light will not result in increased production. Most horticulturists use a unit that measures light at any instant in micromoles (umol) per square meter (m^{-2}) per second (sec^{-1}) of PAR. This unit is called Photosynthetic Photon Flux Density (PPFD). It measures the number of photons (individual particles of energy) used in photosynthesis that fall on a square meter of surface every second. Since this is an instant reading the better unit to use is the daily light integral (DLI) which is the amount of PAR received each day (moles per day). The conversion is 1 $umol/m^2/s^1$ = 0.0864 $mol/m^2/d^1$ of continuous light. In greenhouses the values are normally less than 25 $mol/m^2/d^1$.

Researchers have developed DLI levels for groups of plants classifying them as low-light, medium-light, high-light, and very-high-light crops. Fruit bearing crops like tomatoes, peppers, and

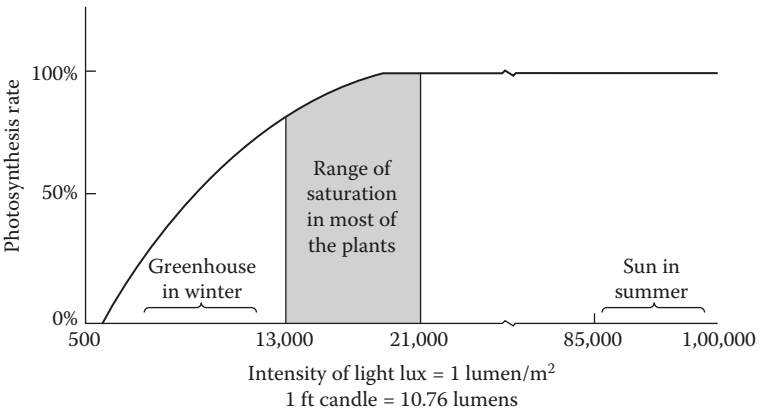

FIGURE 12.44 Graph of photosynthesis activity versus light energy (intensity). (Drawing courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 12.45 T5 fluorescent lights. (From Hydrofarm Horticultural Products, Petaluma, CA. With permission.)

FIGURE 12.46 HID light and fixture. (From Sunlight Supply, Inc., Vancouver, Washington. With permission.)

European cucumbers would lie in the very-high-light crops. The optimum DLI for these crops also varies for the stage of plant growth. Seedlings, for example, require less light from 12 to 16 mol/m^2/d^1, whereas, in full production the DLI should be from 25–35 mol/m^2/d^1. The recommended photoperiod for these vine crops is from 18 to 20 hours per day. For lettuce and leafy greens optimum DLI from seeding to transplant stage is 22 mol/m^2/d^1 and from production to harvest 12–18 mol/m^2/d^1 with an 18- to 22-hour photoperiod.

Sources of supplementary lighting include cool white, high-output fluorescent, high intensity discharge (HID), and light emitting diode (LED) lights as shown in Figures 12.45 through 12.48. HID lighting systems have been the principal lighting in commercial greenhouses. HID lights include high pressure sodium (HPS) and metal halide (MH) lamps. HPS lights provide a lot of red light, whereas, the MH have high emittance of blue light so promote more vegetative growth. Generally, a mixture of HPS with a smaller percentage of MH lights are combined. For any lighting system it is best to work with a light manufacturing company, such as P.L. Light Systems, (www.pllight.com) to plan the layout and mixture of lamps. P.L. Light Systems started operations in 1981 and have specialized in HID light systems. They now also manufacture LED lights and design hybrid LED-HPS lighting solutions. Fluorescent lighting is not used in commercial greenhouses, but is suitable for hobby greenhouses. Phillips, GE Current, Gavita, Heliospectra, and Oreon are a few companies specializing in LED lighting. LED lights consume much less power than HID lights. They are of less weight, generate very little heat, and have long life. An array unit of LED lights that produces an equivalent of a 1,000 watt HID lamp is more expensive than HID lights, but electricity consumption is much less.

Both intensity and quality of light must be taken into consideration in designing a lighting system for a specific crop. LED lights provide red and blue light so are well balanced for vegetative and flowering plant growth. LED arrays, having various combinations of white, red, and blue LED lights within a reflector unit are most suitable to greenhouse lighting (Figure 12.47). Top light fixtures are those that are attached to the greenhouse structure above the rows of plants (Figure 12.48). These lights give a hybrid spectrum of white, red, and blue wavelengths that are better than HID lights.

Philips manufactures both top light and intercrop lighting LED systems. Top lighting is available as compact rectangular units and linear reflectors that are hung or mounted above the plant rows on the greenhouse structure.

GE Current, a Daintree company, offers top lighting LED growing systems for greenhouses and indoor farms. The top lights are called *Arize Element*^{R} (Figures 12.47 and 12.48). The *Arize Element L400* is for photoperiod extension and low DLI crops. The *Arize Element L1000* has the same amount of light output as a 1,000W HPS fixture and claims to use only 40% of the energy. That unit would be for crops with higher DLI and generally used instead of 1,000W HPS fixtures. The units are hung from an overhead greenhouse structural member. The power supply may be located

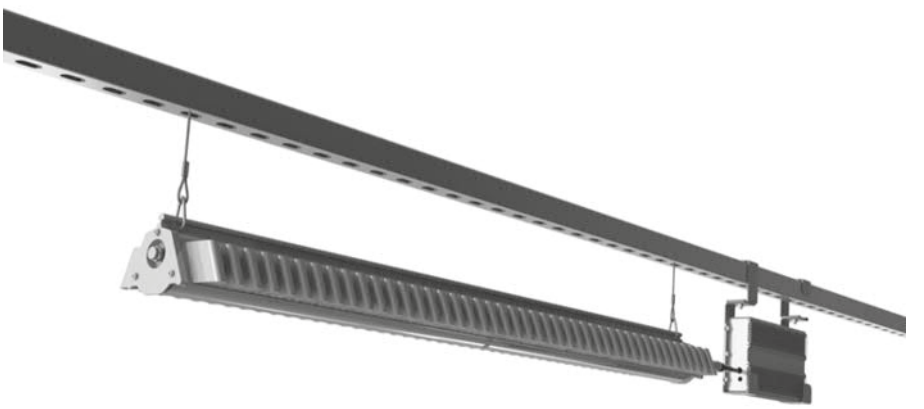

FIGURE 12.47 Current's *Arize Element*^{R} L1000 top light. (From GE Current, a Daintree company, Cleveland, OH. With permission.)

FIGURE 12.48 Current's *Arize Element*^{R} L1000 top light. (From GE Current, a Daintree company, Cleveland, OH. With permission.)

side-by-side to the light fixture; or above the fixture, where the light fixture is located below to allow closer distance from the fixture to the crop with various support cable lengths. A third is a triangular configuration where the light fixture is suspended from the power supply with cables.

Gavita also makes an LED top light, which they claim is a 1:1 HPS replacement. P.L. Light Systems makes a top light, "HortiLED TOP 2.0" that is designed as either a full LED source of light or in combination with HID luminaires as a hybrid lighting system.

Interlighting systems are specifically designed for vine crops like tomatoes, peppers, and cucumbers that benefit from additional light within the crop canopy due to mutual shading from the plant growth above. Placing the lighting within the canopy of vine crops focuses light on the flowers and fruit of the plants to increase yields (Figure 12.49).

Blue light combined with red light during seedling stage reduces stem elongation and increases biomass and fruit production. Research has shown that tomato seedlings grown under supplemental lighting that included blue light (about 10%) had thicker hypocotyls with larger leaves and more dry weight compared to those grown under red light alone. These healthy seedlings result in increased yields.

In commercial greenhouses if a grower is going to produce his own seedlings and green graft, locate the lighting in a specific seedling area of the greenhouse. Green grafting lighting for peppers is the same as for tomatoes. During production they also benefit from similar light to that of tomatoes.

Light sensors within the greenhouse relay to the central computer to control the supplementary lighting periods. The correct amount of supplementary lighting provided to crops saves energy and keeps plant growth rates more steady to avoid any slow growth. The light sensors measure the light levels within the greenhouse and send values to a DLI control in at central computer that calculates the optimal amount of supplementary light needed for the specific crop. It measures ambient light in the greenhouse and activates the fixtures throughout the day to reach a set DLI target. This system provides only the amount of light plants use without any wasted excess light, thus saving energy. The objective is to provide a steady amount of PAR light over the DLI period. If, for example, the ambient light outside the greenhouse is under the needed DLI, the lights can

FIGURE 12.49 Intercanopy lighting of tomatoes.

come on to maintain a steady level of DLI within the greenhouse. This could compensate for low light levels due to cloudy weather when the light intensity is less than optimal at a given time during the day.

This type of light sensor does not control shade systems. Another type of PAR sensor, such as that of Priva, measures PAR values and feeds the information back to the central computer that operates the shade curtain system to regulate light levels within the greenhouse. This is to reduce very high light levels by use of shading and reduce solar radiation causing rising of temperatures. Hoogendoorn also has a PAR sensor that sends information to the central computer to optimize control of lighting, CO_2 dosage, and shading screens.

12.7 COMPUTER AUTOMATION

Environmental conditions within the greenhouse and fertigation in modern greenhouses are controlled by the use of sensors within the crop sending data to a central computer that has preset parameters. In addition, outside weather conditions are monitored by a weather station. The weather sensors include outside temperature, solar, wind speed, wind direction, precipitation, RH, heat radiation, and precipitation intensity that also detects snow. A greenhouse meteorological station is standard equipment for most growing operations.

The temperature sensor assists the central computer to control heating, ventilation, and screens. Solar radiation sensor provides information to the computer to control heating, ventilation, screens, and irrigation. Wind speed measurements are important in regulating air vents, heating, and energy screens. Limiting some of the opening of roof and/or sidewall vents during high wind velocity can prevent damage to the greenhouse structure and crop. The wind direction sensor is especially important for greenhouses having roof vents on both sides of the ridge. Depending on wind direction it determines whether one side of vents can be opened or both for optimum inside climate. It also assists with shading and irrigation. The precipitation sensor operates the vents to prevent moisture from entering the greenhouse and assists in closing vents for heating. The precipitation intensity sensor signals threats of flooding and snowfall. The outside RH sensor influences the heating and ventilation to reduce RH within the greenhouse or with low RH outside less ventilation and operation of a fogging system if present. The outside RH sensor will be coupled to an inside RH sensor to compare the two in order to make a decision on the operation of the vents, air circulation, and heating within the greenhouse. The heat radiation sensor measures the heat radiation losses from the greenhouse to the ambient air. On clear days the energy loss is greater than under cloudy conditions. To compensate for the greater heat loss during clear days screens can be closed sooner. Thus, the control of the energy screens is adjusted for less or more energy loss to keep temperatures more stable within the greenhouse and at the same time save energy.

Priva sells several specific monitors, "TopCrop Monitor" and "Root Optimizer." The "TopCrop Monitor" measures plant temperature by use of an infrared camera and relates it to greenhouse temperature. The theory is that plant activity is closely related to plant evaporation. When stomates are open and CO_2 exchange is taking place these plant spores will be evaporating water to cool the plant surface. If the level of evaporation, for example, is very low, it indicates that air exchange is not optimally taking place as the stomates would not be fully open. Monitoring this crop activity gives information to the central computer that can control heating, ventilation, screens, overhead misting for cooling and humidification and regulate CO_2 injection. As a result, overheating by water stress or crop condensation can be avoided.

The "Root Optimizer" senses moisture levels within the growing substrate. It measures a number of representative plants. The slab weight, water input, and leachate are recorded. To obtain optimum moisture balance in the substrate, information to the central computer determines the irrigation start times and duration. Data is based upon climate conditions, time of day, the correct moisture level,

transpiration, and crop stage. The objective is to maintain an optimum air to water ratio in the substrate for the crop's water uptake at a given time. While these sensor feedback systems to a central computer are part of the overall control of environmental conditions within the greenhouse, other automation systems are involved in the crop production processes.

12.8 CROP PRODUCTION AUTOMATION

Automation has been developed for crop tasks from sowing, transplanting, plant training to harvesting and packing. Seeds are sown with automatic seeders; robotic machines can transplant crops like lettuce to their final growing systems (Figures 6.18 and 6.19). Some lettuce operations are fully automated from sowing of seeds to harvesting, such as Green Automation Systems (Section 6.8) and (Figures 6.36 through 6.69). Transportation of tomatoes, cucumbers, peppers, and eggplants from the greenhouse crop to the packing facility are highly automated with customized carts that are moved and guided to the packing area by an unmanned chain track system. Presently robotic machines have been designed and are being tested for training plants, in the removal of side shoots and lower leaves of tomatoes, and harvesting of tomatoes and peppers. Electric hand tools for clamping vine crops, such as tomatoes, peppers, and cucumbers to support strings have successfully been introduced.

Seed sowing machines have been standard equipment in vegetable, flower, bedding plant, and nursery production for many years. There are many makes and models available to best suit the needs of the crop and the volume of daily sowing required in an operation. A tubeless vacuum seeder, for example, is Growing Systems, Inc. Vandana seeder. This seeder uses a vacuum to fix the seed to a specific plate that corresponds to the seedling tray configuration. The operator must turn the plate over on top of the tray containing the substrate and turn off the vacuum to release the seeds to the tray below. Several trays per minute can be sown with this machine. This machine is fine for small greenhouses, but large greenhouse propagators who sow thousands of trays a day require a more sophisticated machine that is capable of doing so. Usually a complete sowing line of machines is combined. A flat filler that places a soilless or soil substrate from a hopper into the trays as they pass on a belt, then to a dibbler machine that puts impressions in the substrate to receive the seeds, to the sowing machine that drops the seeds into each tray cell, and finally followed by a watering machine that moistens the substrate. Some of the larger equipment can seed 1,200 trays per hour. Blackmore Company, Inc., manufactures numerous sizes of automated medium filling and seed sowing equipment for pots and trays with capacities up to 12,000 pots per hour.

Tomatoes require weekly deleafing, removal of lower leaves, to promote ripening and prevent high RH within the crop, especially when the plants are lowered and leaned. This is very labor intensive. Priva developed a "deleafing robot" that through vision detects the leaves to be removed and cuts them close to the stem to prevent possible disease infection. A cutting module is mounted on a robot arm which moves through the crop as the machine moves down the aisles.

It has vision technology that determines quickly the position of the leaves. The economic viability of this robot is dependent on the number of leaves per hour that can be removed and that it does not damage or contaminate the plants.

A number of harvesting robots have been designed for picking tomatoes and bell peppers. MetoMotion, an Israeli company, has designed a harvesting robot called GRoW (Greenhouse Robotic Worker). It has a "3D Vision System" that detects ripe tomato fruits and their location on the plants. It can also perform other tasks such as pruning and pollinating.

Root AI, a US company, has designed an agricultural robot that is currently in commercial operation. "Virgo" is mobile, and has sensors and cameras for detecting ripe tomatoes ready to harvest. They now have multiple harvesting contracts across North America and are beginning paid commercial operations. This is a big step for them in making the robot in demand in the industry. It gently

FIGURE 12.50 Virgo of Root AI tomato harvesting robot. (From Root AI, Woburn, MA. With permission.)

FIGURE 12.51 Robotic harvester of cucumbers. (From Root AI, Woburn, MA. With permission.)

twists the tomatoes off the plant trusses and placing them into a catchment gutter, where they roll to a box below without bruising (Figure 12.50). Virgo is also capable of picking cucumbers and strawberries (Figures 12.51 and 12.52). The robot moves on tracks in the plant aisles.

In 2021 AppHarvest, a US greenhouse company, acquired Root AI. AppHarvest states that the technology will enable data collection by the robots that can help to evaluate crop health, predict yields, and optimize the overall operations of the greenhouse facility.

To enable the robot to harvest different crops, the hand is changed to meet the task of picking specific crops, but the software package that orchestrates computer vision, planning, and dexterous harvesting remains the same. They state, "This is core to the company's technology thesis, which

FIGURE 12.52 Virgo of Root AI harvesting strawberries. (From Root AI, Woburn, MA. With permission.)

is to create a universal AI software platform that can perform complex physical tasks on multiple crops just as a person can." This AI design is the reason for the robot to work cross crop, a first in the industry. As the robot travels the greenhouse crop aisles it analyzes crop positions and fruit ripeness and then uses its specialized "gripper" to pick. It also has lights so that it can harvest at night.

In the Netherlands, a pepper harvesting robot called the "Sweeper" is being tested with assistance from some pepper growers in conjunction with the University of Wageningen, and several other research organizations. It has a grappling arm that holds the detected ripe fruit and then cuts it off the plant. The arm places the pepper in a fruit collection container. It takes about 30 seconds to harvest a pepper. That is still much slower than what a worker can harvest, so the machine must be improved to enable it to harvest faster than it presently is capable of if it is to eventually become economically viable for use in a greenhouse. Further research and designing is underway.

Drones are being tested to monitor plant growth and stress in greenhouses. They can monitor temperature, RH, CO_2, and luminosity. Another drone design is being evaluated for its ability to pollinate tomatoes. Using a camera it detects flowers and then vibrates the truss of flowers with a burst of air taking pictures of the flower to show the pollination success. Research is underway to test the use of drones for pollination of various crops. Some researchers believe that drones may be employed in various tasks in commercial greenhouses in the future.

12.9 HARVESTING, TRANSPORTING, GRADING, AND PACKING AUTOMATION

A very modern facility of packing is exemplified by Eurofresh Farms (NatureSweet). Loose tomatoes are harvested in tote bins, whereas TOV are harvested directly into the final packing boxes. They are transported down the growing aisles on carts, that run on the heating pipes, to the central greenhouse passage way. There they are placed on picking carts to transport them to the packing facility (Figure 12.53). The cart passes over an electronic scale to weigh the tomatoes. The picking carts are towed by an airport baggage car that allows many carts to follow behind. Once they reach the packing facility, they are lined up in rows (Figure 12.54). The carts are then pushed by hand to a machine that pushes all of the boxes from the cart and places them so that another machine can pick up one tier of the boxes (five boxes) and place them on a belt taking the boxes to the grading and packing area (Figures 12.55 through 12.57). The produce then enters a refrigeration room.

FIGURE 12.53 Picking carts transporting tomatoes in boxes to packing facility. (From Eurofresh Farms, Wilcox, AZ. With permission.)

Eurofresh Farms claimed they were producing 75 kg/m^2/yr (15.3 lb/ft^2/yr) (50 lb per plant per year using the conversion of 3.3 plants per square meter).

Harvesting and packing facilities differ with most greenhouse operations, but the objective is to make it as efficient and least labor intensive as possible. As described above, TOV tomatoes are handled in a specialized manner that is somewhat different from beefsteak and other types of tomatoes. For example, Houweling's Group, Camarillo, California uses the same type of picking carts as Eurofresh Farms, but beefsteak and loose tomatoes are harvested in tote bins and transported by carts towed by electric or natural gas airport tractors to a central packing facility, where they are washed, graded, and packed. The tomatoes are floated into the packing facility and then dried before being graded and finally packaged (Figures 12.58 through 12.60). The floating trough has a U-shaped corner to help push the tomatoes together so that they will all enter the packing system consistently without gaps so that workers have a steady supply to package.

Beefsteak tomatoes are packed according to size, so they look uniform (Figure 12.61). TOV may be packaged in open boxes or in sacks that are then packed in boxes (Figures 12.62 and 12.63).

FIGURE 12.54 Picking carts lined up in the packing facility. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 12.55 Machine lifts boxes from picking carts and places them on the grading-packing belt. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 12.56 The machine lifts the cases of tomatoes from the picking carts. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 12.57 Boxes of tomato-on-vines (TOV) in route to grading-packing area. (From Eurofresh Farms, Wilcox, AZ. With permission.)

FIGURE 12.58 Tote bins with loose tomatoes are dumped into a water trough to float to the packing facility. (From Houweling's Group, Camarillo, CA. With permission.)

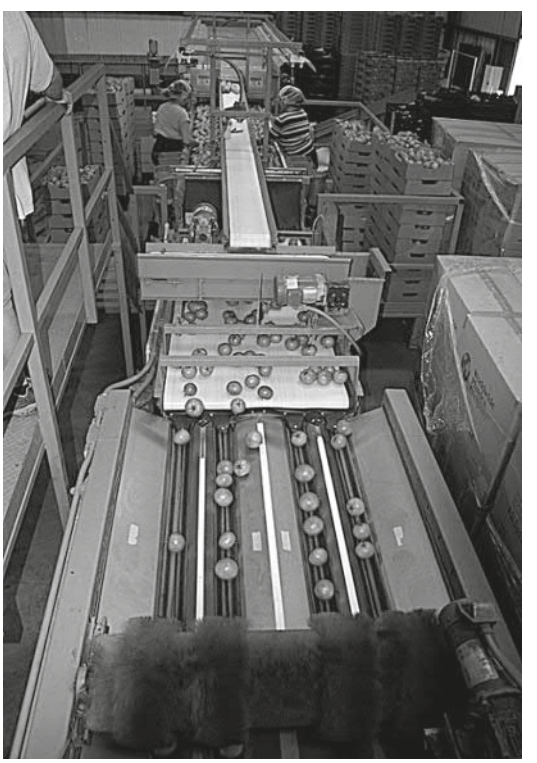

FIGURE 12.59 Tomatoes being dried. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 12.60 Grading and packaging of beefsteak tomatoes. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 12.61 Large grade beefsteak tomatoes in panta packs in cases. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 12.62 Tomato-on-vine tomatoes packed in boxes. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 12.63 Tomato-on-vine packed in net sacks. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 12.64 Large cold storage where tomatoes are stored before final grading. (From Flavorite, Warragul, Victoria, Australia. With permission.)

FIGURE 12.65 Pallets of tomatoes in line for unloading onto the packing-grading conveyor belt. (From Flavorite, Warragul, Victoria, Australia. With permission.)

Flavorite, Warragul, Australia, harvest tomatoes into tote bins in the greenhouse where they are also initially graded and then towed in wheeled bins to the packing cooler. Truss tomatoes are placed in boxes in the greenhouse when harvested, so in effect are mainly graded there. Flavorite also contracts growers for other tomatoes, such as cherries and specialty peppers. They store all of these products in a large cold storage facility (Figure 12.64) before it goes through the grading and packing processes. The pallets of boxed tomatoes enter a caged hoist mechanism that lifts the pallet to remove one layer at a time onto a conveyor belt that transports

FIGURE 12.66 The hoist lifts stacked boxes of tomatoes and removes one tier at a time onto the packing conveyor belt. (From Flavorite, Warragul, Victoria, Australia. With permission.)

FIGURE 12.67 Packing grading facility. Note: The boxes of truss tomatoes enter from the hoist to conveyor on the right. (From Flavorite, Warragul, Victoria, Australia. With permission.)

them to the final grading area (Figures 12.65 and 12.66). Once there, workers pull out any culls or green tomatoes and can add riper ones to the final pack (Figure 12.67). Only small adjustments are made, if necessary, to the trusses as they pass in the final packing area. All green ones are placed in a separate bin and are allowed to ripen before shipping them as single tomatoes in a package.

As a general guideline the packing, grading, storage facility (header house) should be about 4% of the total greenhouse area. In the case of Flavorite, their packing facility is about 1 ha (2.5 acres in area within the 26-ha (64-acre) greenhouse operation.

FIGURE 12.68 Carts with bins of peppers coming in from harvesting pulled by tractor unit. (From Flavorite, Warragul, Victoria, Australia. With permission.)

FIGURE 12.69 Bin on right dumping peppers onto packing conveyor belt. (From Flavorite, Warragul, Victoria, Australia. With permission.)

Peppers are picked into large stainless steel bins that are on tires and towed by a type of tractor to the cold storage (Figure 12.68). Bins enter a hoist machine that dumps the peppers on a conveyor belt that takes them to the grading/packing lines (Figure 12.69). They grow red, green, and yellow bell peppers for three-pack color combinations. Once placed in a clamshell container a machine seals the top with stretch film (Figure 12.70) and final product for sale in Coles and Woolworths supermarkets (Figure 12.71). The harvesting packing processes are becoming more automated as labor is a high cost and often hard to find. In Australia, Flavorite must abide by labor laws, which is about $27 AUD per hour with benefits. They have 240 employees, many of whom are from Taiwan.

FIGURE 12.70 Clamshells of combo packs of peppers entering machine for stretch seal covering. (From Flavorite, Warragul, Victoria, Australia. With permission.)

FIGURE 12.71 Three-color combo pack of bell peppers. (From Flavorite, Warragul, Victoria, Australia. With permission.)

In a planned future expansion Flavorite will install an automated cart chain system in the central passageway, similar to the FormFlex Metazet, to transport the product to the packing facility.

FormFlex Horticultural Systems and FormFlex Automation USA market MTZ products (Metazet) such as the lift carts that travel on the heating pipes. A rechargeable battery operated "M-Truck" is a tractor unit that tows the picking carts. Various models are sold by FormFlex. They can customize carts to be used in conjunction with the M-Truck. For large greenhouse operations, an MTZ chain track system has been developed as an unmanned chain track system for harvesting. It is an in-floor chain track system. Harvesting carts from the crop aisles are connected to the chain in the central passageway. The chain track is installed as a slotted track with a chain in the main passageways and packing facility of the greenhouse operation (Figure 12.72). Peppers, eggplants, and cucumbers are

FIGURE 12.72 Carts moving in the central passageway on the chain track system. (From FormFlex/Metazet Zwethove B.V., The Netherlands. With permission.)

FIGURE 12.73 Bins for harvesting peppers and cucumbers travel on the chain track system. (From FormFlex/Metazet Zwethove B.V., The Netherlands. With permission.)

harvested into bins that move on the track system (Figure 12.73) that travel unmanned to the packing facility where they are transferred to the grading belt (Figures 12.74 through 12.76).

Cucumbers must be shrink wrapped to prevent their losing moisture. This is done with special machines as shown in Figures 10.20 and 10.21.

The chain track system has been installed in greenhouses worldwide for ornamentals, flowers and vegetables. Advantages of this system include a continuous supply of carts to the packing facility, a reduction in labor costs, and return of empty carts automatically to the production area. Many automation systems, such as this are being developed to reduce labor costs and increase efficiency

FIGURE 12.74 Peppers in large bins are unloaded automatically. (From FormFlex/Metazet Zwethove B.V., The Netherlands. With permission.)

FIGURE 12.75 Eggplants in tote bins are automatically unloaded. (From FormFlex/Metazet Zwethove B.V., The Netherlands. With permission.)

of greenhouse operations. We will continue to see this in the future, with trends toward robotics in planting, harvesting, transporting, and packing.

Green Automation is a company in Finland, with a subsidiary in the US that makes two automation systems: the "Living Lettuce System" for growing lettuce heads and herbs; and the "Baby

FIGURE 12.76 Tomatoes in cases are transferred to a belt to the packing area. (From FormFlex/Metazet Zwethove B.V., The Netherlands. With permission.)

Leaf Lettuce System" for baby leafy greens such as leaf lettuce, bok choy, mustard greens, kale, and arugula. This system and Hortiplan are described in Chapter 6.

Automation is now the focus in all aspects of greenhouse growing, harvesting, and packing as labor is getting more expensive and difficult to find. With the covid-19 pandemic in 2020–21 the need for safe product is of prime importance in the growing and handling of produce. With the assistance of automation, human handling of product is greatly reduced. This "hands free" produce has a great advantage over the traditional labor-intensive field-grown crops that have caused disease outbreaks in the past from unsanitary harvesting and handling. Clean produce demands a higher price in the marketplace, making automated growing operations very profitable with increasing demand.

12.10 RETRACTABLE ROOF GREENHOUSES

In many areas of the world complete environmental control systems are not needed. In tropical climates where relative humidity and temperatures are high, the protection needed is for prevention of rain damage. Fully closed greenhouses would be at a disadvantage in tropical climates of high solar energy combined with high temperatures. In a closed greenhouse cooling systems do not function efficiently with a combination of high temperatures and high relative humidity. Temperatures within the greenhouse would exceed those of ambient levels and be non-optimal for many crops.

A greenhouse with a retractable roof is the answer to growing in tropical areas. This type of greenhouse would be covered at night and/or unfavorable ambient conditions such as heavy rains and winds. During the day with high solar energy and high humidity the roof would open to allow

conditions within the greenhouse to closely match the ambient levels. The movement of the retractable roof is operated by a computer system monitoring ambient conditions. A retractable roof greenhouse permits conditions for the growing of many crops, including vegetables and fruiting trees.

Many crops such as lettuce, tomatoes, peppers, and strawberries are grown in the mountains of tropical climates where weather conditions are a little more temperate. In these areas, however, rainfall is much greater than at lower elevations. As a result, severe damage may occur from moisture on the crop. Day-time weather conditions are normally very favorable to growing these crops, so exposure to the ambient atmosphere at that time is beneficial to the crop. A retractable roof greenhouse would be the solution to prevent damage by rainfall. At the same time night temperatures in the mountainous regions may fall below optimum levels. The greenhouse roof closing at night would assist in maintaining more optimum temperatures and reduce moisture on the crop when the relative humidity is very high.

Some cherry growers in New Zealand (Figure 12.77) and Tasmania as well as growers of tomatoes, peppers, lettuce, and herbs in Australia are using retractable roof greenhouses. The retractable roof houses protect vegetable crops and cherry trees against low night temperatures and potential frost damage to the cherry blossoms in the early spring. Using a retractable roof greenhouse, the crop comes into production much earlier than crops outside in ambient conditions. Cherry trees can come into production within a few years of planting with a special training technique of the trees. At the same time the annual production is more than a month earlier than the same plants outside. This is a marketing advantage in that the highest prices for the fruit are obtained in the early part of the season when there is no competition from outdoor production.

A retractable roof greenhouse prevents rain from moistening the ripening fruit close to and during harvest when rain causes serious crop loss through fruit splitting. The greenhouse is also a deterrent to birds entering the crop as birds outside cause significant losses to ripening fruit.

Using a trellis training system reduces labor costs as ladders are not needed to harvest the cherries. Prevention of rain on the blossoms prevents brown rot infection. Overall less pesticides and fungicides are applied.

FIGURE 12.77 Cravo retractable roof greenhouse of 3.5 ha with 5-mo old cherry trees. Note: The anchor cables set in concrete. (From Clyde Orchards, Clyde, New Zealand. With permission.)

FIGURE 12.78 Cherry trees 5 mo old. Note: The retractable roof is about 30% closed and the side wall is about 30% open. (From Clyde Orchards, Clyde, New Zealand. With permission.)

Outdoor cherry trees take 4–5 yr to start fruiting after planting. With a retractable roof the cherry trees will start bearing 1–2 yr sooner than outdoor trees. Combining the retractable roof greenhouse with a special trellis training system will bring the trees into bearing within a few years (Figure 12.78). Branches are partially cut so they may be attached horizontally by plastic clips to trellis wires. Cuts above the node promote buds to form new branches. As new shoots develop they are bent down and tied to the trellis wires (Figure 12.79). After 2 yr of bearing the older branches are removed and replaced with the newer branches. This is a training technique similar to the renewal umbrella training of European cucumbers in greenhouses. Cherries can be brought into production within two years.

Cravo Equipment Ltd. in Brantford, Ontario, Canada (www.cravo.com) is a leading manufacturer of retractable roof greenhouses. They have projects worldwide in all types of climates with many crops.

The greenhouse structure is of galvanized steel with gutter height of 4–5 m to allow adequate natural ventilation. The sidewalls have motorized roll up polyethylene covers. The structures are secured with cables set into one cubic meter concrete anchors to resist strong winds (Figure 12.77). With sensors and computer control algorithms temperature is controlled by automatically operating the roof, side walls, and misting system. The control system also regulates irrigation and fertigation with use of an injection nutrient system. The control system includes an outside weather station that monitors temperature, wind speed, wind direction, rain, and barometric pressure. These data with indoor sensor data of air temperature, humidity, soil moisture enable the computer system to regulate the greenhouse components to maintain optimum growing conditions for the specific crop.

Reid Fruits in Tasmania, Australia, claimed in early 2020 they achieved a 140% increase in yields under a Cravo retractable roof greenhouse compared to their outdoor field production. The pack out was 95–98% No.1 grade with the *Kordia* variety. The fruit was clean and firm with no losses because of cracking or wind scars. This structure is the Cravo retractable orchard covering system (Figure 12.80). They said yields were 17 T/ha under the Cravo house compared to 7 T/ha with the

FIGURE 12.79 Cherry trees 1.5 yr old with new shoots bent down to be attached to the trellis wire horizontally. (From Clyde Orchards, Clyde, New Zealand. With permission.)

FIGURE 12.80 Cravo Retractable Orchard Covering System over cherries, Reid Fruits, Tasmania, Australia. (From Cravo Equipment Ltd., Brantford, Ontario, Canada. With permission.)

outdoor crop. They attributed the increase in yield partially to protection under the Cravo house from frost and rain during pollination.

Cravo retractable roof greenhouses are in use in various locations of Australia growing lettuce, tomatoes, and peppers. Fresh Technique in Hanwood, NSW, Australia has 12,000 m^2 (129,000 ft^2) of lettuce, bok choy, kale, basil, spinach, arugula, chard, watercress, parsley, and other herbs (Figure 12.81). They harvest 50,000 plants weekly. They are growing in a moveable NFT gutter system. This is one type of house by Cravo, a retractable cooling house (Model X-Frame). This type of house can also be used as an automatic retractable field covering system. Cravo manufactures four types of houses. A second type is a retractable greenhouse with retractable shading/heat retention curtain system and retractable insect screen (Figures 12.82 and 12.83). Another is a flat roof field covering system (Figure 12.84). There is a retractable A-frame greenhouse with automatic blackout curtain system for the growing of cannabis (Figure 12.85).

FIGURE 12.81 Cravo retractable cooling house with lettuce. Note: The roof is fully open. Fresh Technique, Hanwood, NSW, Australia. (From Cravo Equipment Ltd., Brantford, Ontario, Canada. With permission.)

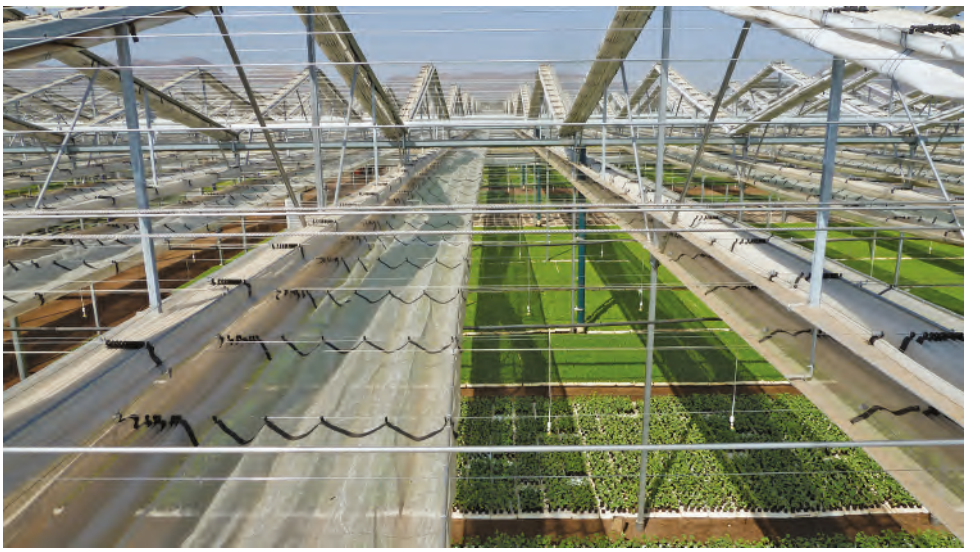

FIGURE 12.82 Cravo retractable greenhouse with shading/heat retention curtain system and insect net. Multi Plant Seeding Nursery, Britts, South Africa. (From Cravo Equipment Ltd., Brantford, Ontario, Canada. With permission.)

FIGURE 12.83 Cravo retractable greenhouse with internal curtain system (Model X-Frame) with tomatoes. LaManna Premier Group, Lancaster, VIC, Australia. (From Cravo Equipment Ltd., Brantford, Ontario, Canada. With permission.)

FIGURE 12.84 17 ha retractable Flat Roof Field Covering System over blueberries. Bloom Farms, Amatitan, Mexico. (From Cravo Equipment Ltd., Brantford, Ontario, Canada. With permission.)

FIGURE 12.85 Cravo retractable A-Frame greenhouse with automatic blackout system over cannabis. (From Cravo Equipment Ltd., Brantford, Ontario, Canada. With permission.)

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13 Other Soilless Cultures

13.1 INTRODUCTION

Many other methods of soilless culture are being used successfully. Some of the media used are peat, vermiculite, perlite, pumice, rice hulls, and plastic Styrofoam. Often mixtures of these media are used in various proportions. Growing trials with various mixtures determine which proportions are most suitable to the plants in question. For example, flowering potted plants such as chrysanthemums, poinsettias, and Easter lilies and tropical foliage plants can be grown well in mixtures of peat–sand–pumice in a 2:1:2 ratio.

13.2 MEDIA

13.2.1 Peat

Peat consists of partially decomposed aquatic, marsh, bog, or swamp vegetation. The composition of different peat deposits varies widely, depending on the vegetation from which it originated, the state of decomposition, mineral content, and degree of acidity (Lucas et al., 1971).

Of the three types of peat – moss peat (peat moss), reed sedge, and peat humus – peat moss is the least decomposed and is derived from sphagnum, hypnum, or other mosses. It has a high moisture-holding capacity (10 times its dry weight), is high in acidity (*p*H 3.8–4.5), and contains a small amount of nitrogen (about 1.0%) but little or no phosphorus or potassium. Peat from hypnum and other kinds of mosses breaks down rapidly, as compared with sphagnum, and is not as desirable. Peat from sedges, reeds, and other swamp plants also decomposes rapidly.

Sphagnum moss is the dehydrated young residue or living portions of acid-bog plants in the genus *Sphagnum*, such as *S. papillosum*, *S. capillacium*, and *S. palustre*. It is relatively sterile, light in weight, and has a very high water-holding capacity. It is generally shredded before being used as a growing medium.

13.2.2 Vermiculite

Vermiculite is a micaceous mineral, which is expanded when heated in furnaces at temperatures near 2,000°F (1,093°C). The water turns to steam, popping the layers apart, forming small, porous, spongelike kernels. Heating to this temperature gives complete sterilization. Chemically, it is a hydrated magnesium–aluminum–iron silicate. When expanded, it is very light in weight (6–10 lb/ft^3) (96–160 kg/m^3), neutral in reaction with good buffering properties, and insoluble in water. It is able to absorb large quantities of water, 3–4 gal/ft^3 (0.4–0.5 mL/cm^3). It has a relatively high cation exchange capacity and thus can hold nutrients in reserve and later release them. It contains some magnesium and potassium, which is available to plants.

Horticultural vermiculite is graded in four sizes: No. 1 has particles from 5 to 8 mm in diameter; No. 2, the regular horticultural grade, from 2 to 3 mm; No. 3, from 1 to 2 mm; and No. 4, which is most useful as a seed-germinating medium, from 0.75 to 1 mm. Expanded vermiculite should not be pressed or compacted when wet, as this will destroy its desirable porous structure.

13.2.3 Perlite

Perlite is a siliceous material of volcanic origin, mined from lava flows. The crude ore is crushed and screened, then heated in furnaces to about 1,400°F (760°C), at which temperature the small amount

DOI: 10.1201/9781003133254-13

of moisture in the particles changes to steam, expanding the particles to small, spongelike kernels, which are very light, weighing only 5–8 lb/ft^3 (80–128 kg/m^3). The high processing temperature gives a sterile product. A particle size of 0.063–0.13 in. (1.6–3.1 mm) in diameter is usually used in horticultural applications. Perlite will hold three to four times its weight of water. It is essentially neutral, with a *p*H of 6.0–8.0, but with no buffering capacity; unlike vermiculite, it has no cation exchange capacity and contains no minor nutrients. It is most useful in increasing aeration in a mixture since it has a very rigid structure. While it does not decay, the particle size can become smaller by fracturing as it is handled. A fine grade is useful primarily for seed germination, while a coarser type of horticultural grade is best suited for mixing with peat, in equal parts, for propagation or with mixtures of peat and sand for growing plants.

13.2.4 Pumice

Pumice, like perlite, is a siliceous material of volcanic origin. However, it is the crude ore after crushing and screening without any heating process. It has essentially the same properties as perlite, but is heavier and does not absorb water as readily since it has not been hydrated. It is used in mixtures of peat and sand for the growing of potted plants.

13.2.5 Rice Hulls

Rice hulls are the outer husk or shell of the rice grain. After the rice grains are dried, the outer hulls are removed in the milling as a by-product. The rice hulls are thin, feather-light, and pointed in shape similar to rice grains. They do not decompose readily, lasting from 3 to 5 yr. They are neutral in *p*H and have no nutrients. Their smooth surface does not allow them to retain moisture. They are used in the raw state to free up heavy soils to help oxygenate the soils. They can also be used as a hydroponic substrate (Laiche and Nash, 1990). They are mixed with peat or coco coir, usually at 20% of rice hulls. In the past, as described later in this chapter, they can, under some soilless systems, be used by themselves. However, most soilless mixes using rice hulls prefer to use charcoaled rice hulls. This is done extensively in the greenhouse flower industry in Colombia. Rice charcoal is created by burning (smoldering) the rice hulls very slowly. After burning, their structure becomes full of tiny pores, thus increasing their water- holding capacity and capillary action. Also, in this state with their large surface area, they provide sites for beneficial bacteria and other micro-organisms and therefore are an excellent soil amendment.

13.2.6 Soilless Mixtures

Most mixtures contain some combination of sand, peat, perlite, pumice, and vermiculite. The specific proportions of each component used depends on the plants grown. The following are some useful mixtures.

1. Peat:perlite:sand	2:2:1 for potted plants
2. Peat:perlite	1:1 for propagation of cuttings
3. Peat:sand	1:1 for propagation of cuttings and for potted plants
4. Peat:sand	1:3 for bedding plants and nursery container-grown stocks
5. Peat:vermiculite	1:1 for propagation of cuttings
6. Peat:sand	3:1 light weight, excellent aeration, for pots and beds, good for azaleas, gardenias, and camellias, which grow well in acid conditions
7. Vermiculite:perlite	1:1 light weight, good for propagation of cuttings
8. Peat:pumice:sand	2:2:1 for potted plants

In general, pumice, which costs less, may be substituted for perlite in most mixes.

The most common mixtures are the University of California (U.C.) mixes of peat and fine sand, and the Cornell "peat-lite" mixes. The U.C. mixes were derived from the California Agricultural Experiment Station in Berkeley. The U.C. mixes vary from fine sand only to peat moss only, but the mixes that are used more commonly contain from 25% to 75% fine sand and 75% to 25% peat moss. These mixes are used for growing potted plants and container-grown nursery stock. The peat-lite mixes were devised by Cornell University, New York, from equal proportions of peat and vermiculite. They have been used primarily for seed germination, growing of transplants, and for container growing of spring bedding plants and annuals. Some growers have used them to grow tomatoes commercially in beds, similar to sawdust culture.

All of the required minerals must be added to these mixes, and some or all of them are added at the time of mixing. The Cornell peat-lite mixes are considerably lighter in weight than the U.C. mixes, as either perlite of vermiculite weighs about one-tenth as much as fine sand. The peat-lite mixes are made from equal parts of sphagnum peat moss and either horticultural perlite or No. 2 vermiculite.

13.2.6.1 The U.C. Mix

The basic fertilizer additions recommended for a U.C. mix of 50% fine sand and 50% peat moss are given here (Matkin and Chandler, 1957).

To each cubic yard (0.7645 m^3) of mix, add:

2.5 lb (1.136 kg) hoof-and-horn or blood meal (13% nitrogen)
4 oz (113.4 g) potassium nitrate
4 oz (113.4 g) potassium sulfate
2.5 lb (1.136 kg) single superphosphate
7.5 lb (3.41 kg) dolomite lime
2.5 lb (1.136 kg) calcium carbonate lime

The fine sand, peat moss, and fertilizer must be mixed together thoroughly. The peat moss should be moistened before mixing. As the crop grows, additional nitrogen and potassium fertilizer must be provided.

13.2.6.2 The Cornell "Peat-Lite" Mixes

Instructions for three peat-lite mixes are as follows (Boodley and Sheldrake, 1964, 1972; Sheldrake and Boodley, 1965):

1. Peat-lite mix A (to make 1 yd^3 or 0.7645 m^3):
   11 bu (88 U.S. gal) (333 L) sphagnum peat moss
   11 bu (88 U.S. gal) (333 L) horticultural vermiculite No. 2 grade
   5 lb (2.27 kg) ground limestone
   1 lb (0.4545 kg) superphosphate (20%)
   2–12 lb (0.909–5.4545 kg) 5-10-5 fertilizer
2. Peat-lite mix B:
   Same as A, except that horticultural perlite is substituted for the vermiculite.
3. Peat-lite mix C (for germinating seeds).
   1 bu (8 U.S. gal) (30.3 L) sphagnum peat moss
   1 bu (8 U.S. gal) (30.3 L) horticultural vermiculite No. 2
   1.5 oz (42.5 g) ammonium nitrate
   1.5 oz (42.5 g) superphosphate (20%)
   7.5 oz (212.6 g) ground limestone, dolomitic

The materials should be mixed thoroughly, with special attention given to wetting the peat moss during mixing. Adding a nonionic wetting agent such as Aqua-Gro (1 oz/6 U.S. gal water (28.35 g/22.7 L water) initially will aid in wetting the peat moss.

13.2.6.3 Fertilizer, Sphagnum Peat Moss, and Vermiculite Mixture

The Vineland Research Station in Ontario, Canada (Sangster, 1973), uses a slight modification in fertilizer ingredients for addition to a mixture of equal volumes of sphagnum peat moss and vermiculite (50:50 peat-vermiculite) per cubic yard (0.7645 m^3) as shown below.

1.75 bales of 6 ft^3	peat moss
2 bags of 6 ft^3	vermiculite (No. 2)
12 lb (5.45 kg)	ground limestone (dolomitic)
5 lb (2.273 kg)	calcium sulfate (gypsum)
1.5 lb (0.682 kg)	calcium nitrate
2.5 lb (1.136 kg)	20% superphosphate
8–10 lb (3.64–4.54 kg)	Osmocote 18-6-12 (9 mo)
6 oz (170 g)	fritted trace elements (FTE 503)
1 oz (28.35 g)	iron (chelated, such as Sequestrene 330)
0.5 lb (227 g)	magnesium sulfate

Osmocote 18-6-12 provides a continuous supply of nitrogen, phosphorus, and potassium throughout the growing season. FTE 503 slowly releases iron, manganese, copper, zinc, boron, and molybdenum.

Mixing the fertilizer ingredients with the peat-moss mixture can be done in several ways. Small volumes can be mixed with a shovel on a concrete floor. When mixing on a floor, first disinfect the floor area with a solution of five parts water to one part Clorox (5.25% sodium hypochlorite). Spread the fertilizer evenly over the medium and turn the mix back and forth from one pile to another several times with a shovel. A large garbage can is useful for mixing a 2-bu batch. Scoop the mix into the garbage can, pour the mix back onto the floor, and repeat this procedure several times.

A large concrete mixer works well for mixing large amounts. Often commercial growers acquire a "ready-mix" unit from an old concrete truck. This unit can be mounted on a concrete slab and a motor attached to operate it. A series of conveyors can feed in ingredients and also pile the finished product in the potting area of the greenhouse.

If plastic-lined beds are used for the plants, the medium can be mixed directly in the beds. It can be mixed with a padded hoe, taking care not to rupture the plastic liner. For large greenhouses a ready-mix unit should be used, with conveyors conducting the finished product directly to the beds.

Dry peat is usually hard to wet. Adding two ounces (56.7 g) of a nonionic wetting agent such as Aqua-Gro in 10 gal (37.85 L) of water will help wet the peat in 1 yd^3 (0.7645 m^3) of mix. Micronutrients should be dissolved in water, which is then sprinkled over the medium or added directly to the mixer while mixing. For a 2-bu (16-U.S.-gal) (60.6-L) batch, the nutrients can be dissolved in 1 gal (3.785 L) of warm water and then sprinkled over the medium before mixing.

13.2.7 Coco Coir

As discussed in Chapter 11, coco coir is becoming increasingly popular as a soilless substrate. Coco coir is not screened to remove the fibers, so this adds to its porosity and gives better aeration than peat.

In the tropics it can be purchased very cheap by the truckload in bulk form. However, a number of companies in North America compress it into an expandable hard brick. By adding 5 qt (5 L)

of water to each brick of 20 oz (567 g), it will expand to approximately 9 qt (9 L) within 15 min. It has a fluffy texture with a *p*H 5.7–6.3. Most coco coir comes from Indonesia, but future sources could come from South America and Mexico. One precaution to be taken is to check its salt (sodium chloride) content, especially if purchasing bulk coco coir form coastal areas close to the ocean. Also, it may contain residual potassium, so initial nutrient solutions should be adjusted accordingly. It may be mixed with perlite or vermiculite in similar ratios as discussed earlier for peat in peat-lite mixes.

13.3 HYDROPONIC HERBS

The demand for fresh herbs is increasing in the marketplace. Many are now packaged in zip-lock type plastic bags to keep them fresh. "Live" herbs are even more popular. These are clumps of herbs grown in a water culture or an NFT system. Rockwool or oasis cubes can be used to start the plants. They are transplanted to an NFT hydroponic system and grown there for a number of weeks depending on the growth rate of the specific herb. They are harvested as a complete bunch with roots in the growing block. The bunch is placed in a sleeve or rigid plastic clamshell container to maintain freshness at the supermarket.

Some of the more common culinary herbs include anise, basil, chervil, chives, coriander (cilantro), dill, fennel, mint, oregano, parsley, rosemary, sage, savory, sweet marjoram, tarragon, and thyme. Many are grown in the field on a large scale; however, some are particularly suitable for hydroponic greenhouse culture. These include basils (sweet Italian, Thai basil, cinnamon basil, lemon basil, and purple/opal basil), chervil, chives, baby dill, fennel, oregano, sweet marjoram, sage, savory tarragon, thyme, upland cress, and watercress.

Herbs may be grown in a number of soilless substrates such as sand, peat-lite mixes, rice hulls, coco coir, perlite, foam, rockwool, and NFT. However, many are sensitive to moisture levels in their root zone. Basil, for example, does not like a lot of moisture in its crown (but does well in NFT); tarragon requires relatively dry conditions, and mint prefers a lot of water similar to watercress.

13.3.1 Growing Herbs in a Peat-Lite Mix

California Watercress, Inc., Fillmore, California, grew a number of herbs in a peat medium containing 60% peat, 15% sand, 15% fir bark, and 10% perlite. Dolomite lime was added to stabilize the *p*H between 6.0 and 6.5. A wetting agent and a 9-mo formulation of slow-release fertilizer were incorporated into the medium. Mint, chives, thyme, basil, and oregano were grown successfully in the medium.

About 1 acre (0.4 ha) of greenhouses was constructed to grow these herbs hydroponically year-round, but emphasis was on winter production in the greenhouses. Beds 8 ft x 155 ft (2.4 m x 47 m) were constructed of 8 in. x 8 in. x 16 in. (20 cm x 20 cm x 40.5 cm) cement blocks and 4 ft x 4 ft (1.2 m x 1.2 m) pallets (Figure 13.1). Sides were formed using 1 in. x 8 in. (2.5 cm x 20 cm) lumber nailed to the edges of the pallets. This gave a bed depth of 5 in. (13 cm). The beds were lined with chicken wire and 6-mil black polyethylene (Figures 13.2 and 13.3). The chicken wire prevented the black poly from sagging between the spaces of the pallet tops. Small slits were made in the bottom of the poly liner at centers of 16–18 in. (40–46 cm) to allow adequate drainage. The polyethylene liner was stapled along the top edges, sides, and bottom of the beds. Support braces to secure the sides of the beds were nailed every 20 ft (6 m) along the bed length before putting the medium in the beds (Figure 13.4). The medium was moistened before placing it in the beds.

The irrigation system consisted of a central injector and with 2-in.-diameter PVC mains and 1-in.-diameter PVC headers supplying nutrients via "T-tape" drip hoses at 12-in. (30.5-cm) centers (Figure 13.5).

Two headers, one at the front of the beds and the second in the middle are connected to the drip lines so that each set ran only half the length of the beds (about 75 ft) (23 m). The drip tape was

FIGURE 13.1 Beds constructed of cement blocks and pallets. (From California Watercress, Inc., Fillmore, CA. With permission.)

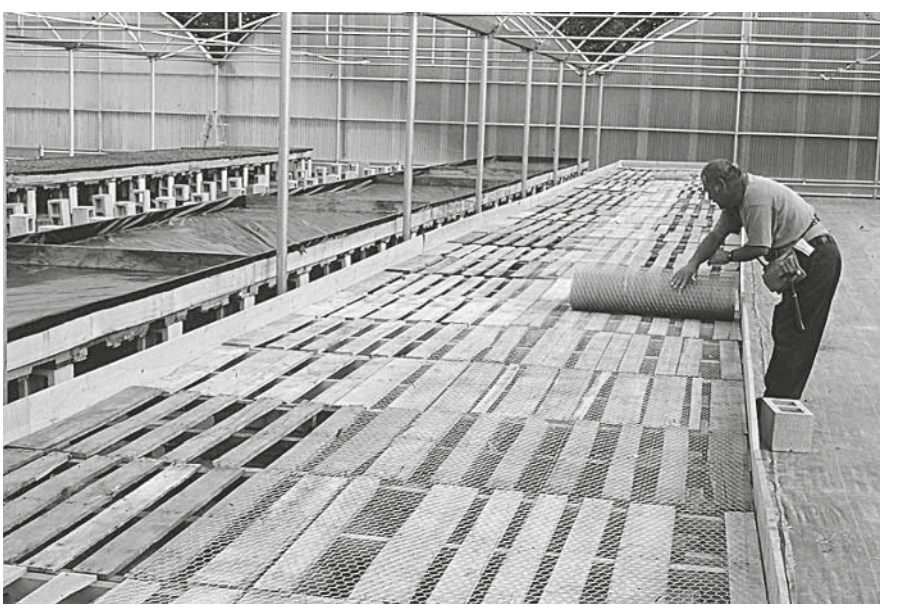

FIGURE 13.2 Beds are lined with chicken wire to support a polyethylene liner. (From California Watercress, Inc., Fillmore, CA. With permission.)

pre-punched at 12-in. (30.5-cm) centers along its length. The irrigation system was operated by two timer controllers. Irrigation cycles were generally every 2–3 d for 1–1.5 h depending on the stage of plant growth and weather conditions. The duration of each cycle was long enough to produce sufficient leaching to flush any salt buildup.

FIGURE 13.3 Black polyethylene liner is stapled to the bed. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 13.4 Placing of a peat-lite medium in the completed bed. (From California Watercress, Inc., Fillmore, CA. With permission.)

Seedlings or rooted vegetative cuttings grown in small pots or trays were transplanted to the beds (Figure 13.6). In some cases, as for chives and mint, field plants were divided and roots washed before transplanting to the beds.

It was expected that since these herbs are perennials, the plants could remain in the beds for several years under continual cropping (Figures 13.7 and 13.8). When the crop needs to be replaced, the medium should be changed as no steam sterilization equipment is available.

FIGURE 13.5 Irrigation ooze hoses, T-tape at 12-in. centers. Chives were transplanted. (From California Watercress, Inc., Fillmore, CA. With permission.)

The greatest problem with this medium is the root buildup. After more than 2 yr of cropping the same plants, a highly compacted root system formed throughout the medium. This reduced oxygenation, with resultant root die-back. The crop should be changed each year, and the medium sterilized or changed to prevent root rots.

Owing to the hard water, containing over 150 ppm of Ca as calcium carbonate and over 50 ppm of Mg as magnesium carbonate, crusting of the medium developed, especially when using overhead sprinkler irrigation. With a drip irrigation system less crusting developed. However, it became necessary to rake the surface of the substrate periodically to loosen it.

While the substrate grew the herbs well for almost a year, eventually salt buildup due to the hard water reduced production. After 2 yr the peat-lite medium was removed and it was substituted with rice hulls containing about 15–20% sand. This medium was placed on top of a capillary matting, which assisted in distributing the solution laterally as the rice hulls have little capillary action.

13.3.2 Herbs in Rice Hulls

As mentioned above, the peat-lite medium accumulated high levels of salt over a period of 2 yr and therefore had to be replaced. In 1999, peat-lite medium was relatively expensive in comparison to rice hulls ($30–$35 per cubic yard vs. $6 per cubic yard).

FIGURE 13.6 Transplanting oregano seedlings. Note: The drip lines were placed immediately after transplanting. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 13.7 First harvest of mint 58 d after transplanting. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 13.8 Oregano, thyme, and mint in beds of peat-lite medium. (From California Watercress, Inc., Fillmore, CA. With permission.)

The beds were constructed somewhat differently from the peat-lite beds. They were built of steel supports with 2 in. x 4 in. treated wood frames and plywood surfaces. Two beds, 4-ft wide by 156 ft (47.5 m), were sloped 2 in. (5 cm) across toward the center and lined with 10-mil black polyethylene (Figure 13.9). Sides were constructed of treated 1 in. x 8 in. boards (2.5 cm x 20 cm).

The system was modified to be recirculating. Plastic gutters or 3-in. PVC pipe were installed in the center where the beds sloped to collect the leachate (Figure 13.10). A capillary matting was placed on top of the polyethylene liner to move the irrigation water laterally as the rice hulls have little capillary action. To prevent the rice hulls from floating into the catchment gutter, a painted, galvanized gyproc corner bead was secured to the bottom edge of the bed next to the gutter (Figure 13.11). The beds were filled with 2 in. (5 cm) of rice-hull and sand mixture (20% sand) (Figure 13.10).

The irrigation system was modified from the existing drip system used with the peat-lite medium. A 0.75-in. black polyethylene hose with 0.5-inch tees placed every 2 ft (61 cm) along its length was located at the high side of the beds (Figure 13.12). It ran both ways for 25 ft (7.5 m) from 1-in. headers located with vertical lines from a tee every 50 ft (15 m) (Figure 13.12). A controller with a solenoid valve on each bed programmed the irrigation cycles. The leachate collected in the gutter returned to a 2,500-gal (9,462-L) cistern outside the greenhouse via a 3-in. return line (Figure 13.13).

The rice hull mixture must be moistened well before adding it to the beds. A portable cement mixer is useful, but it can be mixed by hand on a concrete slab or pieces of plywood. If rice hulls are not thoroughly wetted before placing them in the beds, they will not retain water uniformly, especially if the rice hulls are new. The rice hulls generally contain many embryos that will germinate in the beds as water is applied to the substrate. This grasslike growth must then be weeded by hand. This problem may be reduced greatly by aging the rice hulls several months prior to using it. Moisten the rice hulls with overhead sprinklers for several weeks to germinate the seed. Then, allow it to dry or apply a herbicide (nonpersistent one) to kill the growth. Alternatively, fill the beds with the rice hull substrate, irrigate it to germinate the seeds and then apply a nonpersistent herbicide such as "Roundup." Transplant after 7–10-d.

Mint was the principal crop. It is vegetatively propagated from shoot cuttings. Stick the cuttings in 200-cell trays using a rooting hormone and placing them in a coarse peat-lite medium. Place the

FIGURE 13.9 Lining double beds with black polyethylene. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 13.10 Double beds slope to the center catchment trench. (From California Watercress, Inc., Fillmore, CA. With permission.)

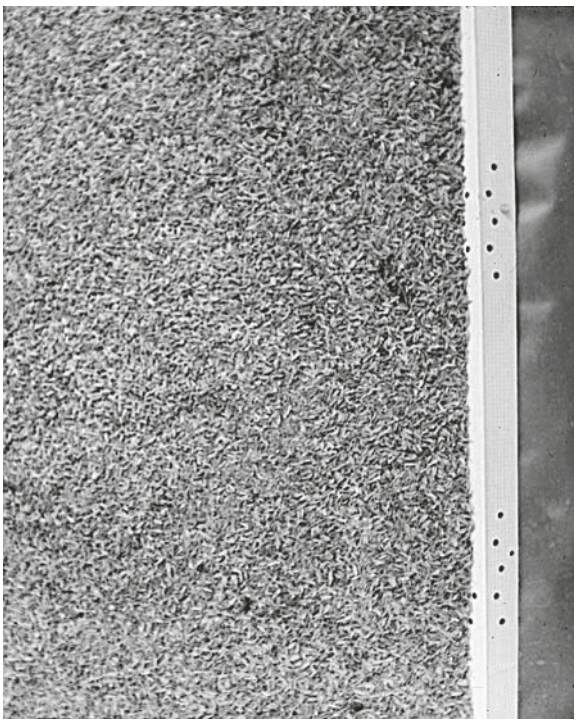

FIGURE 13.11 Gyproc corner next to gutter. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 13.12 Transplanting 4- to 5-wk-old mint cuttings. (From California Watercress, Inc., Fillmore, CA. With permission.)

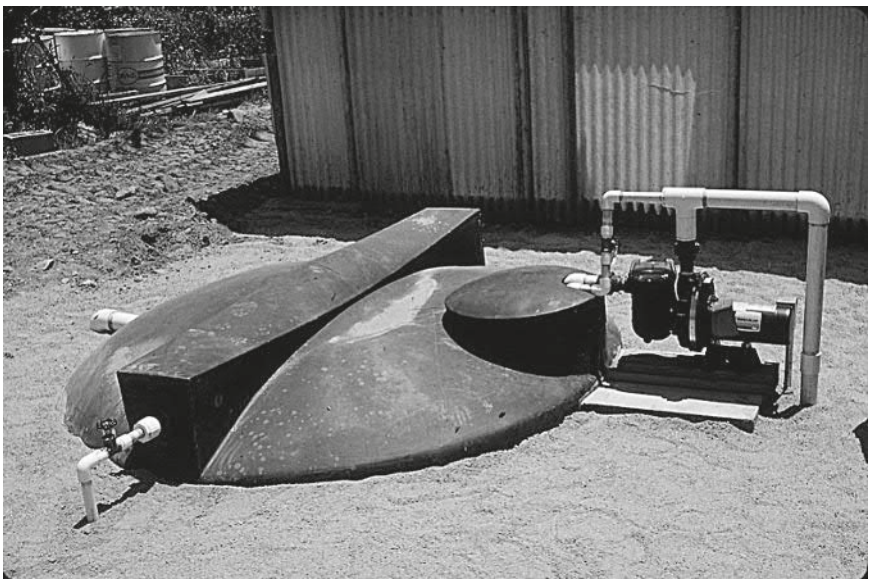

FIGURE 13.13 A 2,500-gal cistern with pump at right. (From California Watercress, Inc., Fillmore, CA. With permission.)

FIGURE 13.14 Mint ready for first cut 31 d after transplanting in rice hulls. (From California Watercress, Inc., Fillmore, CA. With permission.)

trays in a propagation house having overhead misting. Within 4–5 wk the cuttings root and are ready to transplant to the growing beds (Figure 13.12). They are transplanted at 3 in. x 3 in. (7.5 x 7.5 cm) spacing so that a full crop will establish within 3 mo. The first and second harvests (first and second month, respectively) will produce 50–70% of the fully mature harvests (Figures 13.14 and 13.15).

The mint crop, together with the rice hull substrate, needs to be changed every year to maintain high yields. This is done during the summer months when prices are depressed. The key function

FIGURE 13.15 Fully established mint 36 d after previous harvest. (From California Watercress, Inc., Fillmore, CA. With permission.)

of the rice hulls is to keep the surface of the underlying capillary mat dry to prevent fungus gnats, algae, and snails from infesting the substrate. With experience it was found that rice hulls alone without the sand additive was better because the sand settled to the bottom of the rice hulls and impeded the flow of irrigation across the bed. Slightly more depth, up to 3–4 in. (8–10 cm) of rice hulls alone on top of the capillary matting, improved aeration and eliminated pest problems with fungus gnats and snails.

With the rice hulls, initial mint production ranged from 250 to 300 dozen bundles per bed of 1,200 ft^2 (111 m^2). This rose to 450–500 dozen bundles per bed during its optimum growth.

Herbs are sold normally as dozens of bundles, which is a variable measure. The size of bundles is a function of the person harvesting and market demand. When the market is short of supply and good quality, growers may harvest smaller sized bundles, resulting in higher numbers of bundles harvested per lineal foot of bed length. In general, with thyme, oregano, basil, and mint one dozen bundles are equivalent to 1 lb during the summer, while during winter two dozen make up 1 lb.

Owing to bundle size variability and corresponding weight differences, the market now wishes to use weight measurement. The trend is now to market high-quality herbs in attractive packaging for supermarket sales. Bulk sales to restaurants should be in boxes with a plastic bag liner containing 1–2 lb (454–908 grams) of product.

13.4 PERLITE CULTURE

13.4.1 Perlite Blocks and Slabs

Perlite blocks are becoming a competitive alternative to rockwool blocks. They are gaining popularity in the propagation of young tomatoes, peppers, cucumbers, and eggplants. A Belgium company, Willems Perlite NV, claims that millions of these seedlings are grown in perlite. The seedlings in perlite blocks are grown in large nurseries using the ebb and flood system as was described in Chapter 6 (Figure 13.16). They claim that these blocks with their transplants grow more generative

FIGURE 13.16 Pepper transplants growing in perlite blocks in an ebb-and-flood system. (From Willems Perlite NV., Belgium. With permission.)

plants on slabs of perlite, coco coir, and peat. They attribute this growth to the optimum combination of water and air regulation that develops many fine and active roots (Figure 13.17). They state that the blocks do not dry out on other substrates due to their strong capillarity.

Perlite culture is an alternative to rockwool culture (Gerhart and Gerhart, 1992; Munsuz et al., 1989). In Great Britain, it is considered the third most important hydroponic system behind rockwool and NFT. Day (1991) states that it is mainly used in Scotland and the north of England for growing 16 ha (40 acres) of greenhouse tomatoes. At present, rockwool culture is still the most important hydroponic system. In 2008, the largest greenhouse complex in the United Kingdom, Thanet Earth, was begun in East Kent on the Isle of Thanet, near Birchington. When the planned seven greenhouses are completed they will occupy 91 ha or about 220 acres under glass and house 1.3 million tomato, pepper, and cucumber plants. By 2019 they had completed the sixth greenhouse. Each glasshouse in 2021 is powered and heated by Combined Heat and Power (CHP) generators. Besides providing the electricity to light and heat the greenhouses, they provide additional power back to the local grid. Plants are in raised beds with a convection tube below. They use a recirculation close loop hydroponic rockwool system. Collection of rainwater from the greenhouses for storage in large reservoirs supplies about 80% of their water needs. The greenhouses are high-tech Dutch glasshouses using rockwool culture. As a result, with this new operation rockwool remains as the most important hydroponic cultural system in Great Britain.

The perlite-slab system is set up in the same way as rockwool culture, with similar drip irrigation design using an injection system. Seedlings are started in rockwool cubes and transplanted to rockwool blocks several weeks before transplanting to the perlite slabs. The *p*H and EC of the nutrient solution entering and leaving the perlite slabs must be monitored and recorded, and adjustments made to the formulation and watering cycles as required, maintaining an optimum feeding program. The number of cycles, duration of each cycle, formulation, and leachate rate must all be monitored. The leachate may vary up to 25–30% depending on the status of the growing slab and crop performance. About 1–1.5 in. (2.5–4 cm) of solution is maintained in the slab as a reservoir by cutting a slit in the side of the slab facing the irrigation line at a height of 1–1.5 in.

FIGURE 13.17 Large root system with many fine and active roots in perlite block. (From Willems Perlite NV., Belgium. With permission.)

(2.5–4 cm) up from the bottom. Coarse perlite is used as the substrate. After cutting holes in the top of the bag for the plant sites, the rockwool blocks are placed in these positions and a drip line placed at each block.

In 2005, one greenhouse in Naica, Mexico, near Chihuahua, was growing cherry tomatoes in slabs of perlite (Figure 13.18). Their production was very good as can be seen from Figure 13.18.

13.4.2 Perlite Bato Buckets

The use of "bato buckets" for perlite culture originated in Holland. This system permits re-circulation of the solution as the buckets sit on a drainpipe. While the bato bucket system may use substrates other than perlite, such as lava rock, sawdust, peat-lite, rice hulls, or coco coir, the most common is perlite. With sawdust, peat-lite, rice hulls, or coco coir, it would be difficult to recycle the nutrient solution because of salt buildup in the medium. Also, since the siphon mechanism of the bato buckets keeps about 0.5 in. (~1.2 cm) of solution in the bottom of the pot, it would cause aeration problems with media such as sawdust, peat-lite, or coco coir. The bato bucket system is best adapted to perlite and lava rock.

One company in Queretaro, Mexico, Agros, S.A. de C.V., is growing 33 acres (13 ha) of tomatoes successfully in a bato bucket system with a lava rock medium (Figure 13.19).

CuisinArt Golf Resort & Spa in Anguilla is growing about 10,000 ft^2 (approximately 1,000 m^2) of vine crops in a perlite bato bucket system. European cucumbers, beefsteak and cherry tomatoes, peppers, and eggplants are grown in the system (Figures 13.20 through 13.23).

FIGURE 13.18 Cherry tomatoes in perlite slabs.

FIGURE 13.19 Bato bucket system using lava rock substrate. (From Agros, S.A., Queratoro, Mexico. With permission.)

The layout for the bato bucket system is somewhat similar to that of rockwool culture. The main difference is the installation of the drainpipe before setting out the buckets. A white-on-black polyethylene floor liner is laid out once the main drain headers (returns to cistern) have been installed. In the CuisinArt project a vinyl floor liner was placed on top of the underlying substrate before installing the return drains. Six inches (15 cm) of sand fill was placed on top, and finally after placing the pots and drain lines, 3 in. (7.5 cm) of coral gravel was put on top of the sand to give a clean surface (Figure 13.23).

FIGURE 13.20 Beefsteak tomatoes in bato buckets of perlite. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

FIGURE 13.21 Three-month-old eggplants in bato buckets of perlite. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

The bato buckets were placed on top of the drainpipes, which were spaced at 6-ft (1.8-m) centers between the drainpipes, which were the row spacing. The buckets were spaced on the drainpipes at 16-in. (40.6-cm) centers. Placing two tomatoes, peppers, or eggplants per bucket and one European cucumber per pot gives the standard spacing for these crops.

FIGURE 13.22 Peppers 4 mo from seed, ready to harvest. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

FIGURE 13.23 European cucumbers 6 wk from sowing ready to harvest. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

FIGURE 13.24 Placing siphon elbows in bato buckets. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

The bato buckets are made of rigid plastic measuring 12 in. x 10 in. x 9 in. deep (30 cm x 25 cm x 23 cm), as shown in Figure 13.24. Their volume is approximately 4 gal (16 L) if filled within 1 in. (2.5 cm) of the top. They have a 2 in. x 1.5 in. (5 cm x 4 cm) indentation at the back of the base of the pot that lets the pot sit on top of a 1.5-in.-diameter drainpipe. Our experience with cucumbers and tomatoes indicated that the 1.5-in.-diameter drainpipe was too small, causing a lot of root buildup in the drainpipe. The drainpipes were later changed to 2 in. diameter. A 0.75-in.-diameter double elbow forms the siphon from the bottom of the pot into the drainpipe (Figure 13.24). This siphon keeps the moisture level in the pot at about 0.5 in. (~1.2 cm) depth. This reservoir of solution is important in perlite and any type of gravel medium. The siphon drains directly into the drainpipe on which the pot sits at one end. Be careful to use coarse perlite (Figure 13.25) and do not pack it into the bato bucket, as this may plug the drain siphon. Avoid using fine perlite. The pots are staggered one side to the other along the drainpipe at 16-in. (40.6-cm) centers (Figures 13.24 and 13.25).

The drip irrigation system supplies nutrients via 0.5-in. black polyethylene hose having a 0.5-gal/h (2-L) compensating emitter connected to a drip line and stake at the end (Figure 9.15). A special grooved stake that conducts the solution down its length is very useful in directing the solution to each plant. We found that three drip lines per cucumber were needed, while two lines were suitable for tomatoes, peppers, and eggplants. The rest of the irrigation system is the same as for rockwool or sawdust culture employing stock tanks and injectors as illustrated in Figure 13.26, or a central cistern from which the solution could be re-circulated after sterilization.

The bato bucket system grows healthy, highly productive vine crops. Occasionally a few bato buckets become plugged and fill with solution. This occurs if any compaction of the perlite occurs causing the siphon elbow to plug.

13.4.3 Eggplants in Perlite Culture

The author has grown eggplants successfully in bato buckets of perlite at the hydroponic farm at CuisinArt Golf Resort & Spa, in Anguilla, in the Caribbean. The eggplants were sown in 1.5-in. (3.75-cm) rockwool cubes and after 3 wk transplanted to 3-in. (7.5-cm) rockwool blocks. They are

FIGURE 13.25 Filling bato buckets with coarse perlite. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

FIGURE 13.26 Injection system. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

FIGURE 13.27 Train eggplants to two stems. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

transplanted to the perlite system within 5–6 wk from sowing. This initial sowing and transplanting is very similar to tomatoes. Similar to tomatoes and peppers, two plants are placed in each bato bucket. Place a drip line at the edge of the rockwool block of each plant.

The plants are trained vertically with plastic vine clips attached to the string from the overhead support cable. As with peppers, twice as many support strings will be needed than for tomatoes as two main stems per plant are permitted to grow.

Training of the plants is more similar to peppers than tomatoes as they are permitted to bifurcate once to form two stems (Figure 13.27). Similar to peppers, the two most vigorous stems are permitted to grow while any additional ones are removed at an early stage in their growth, usually about 8 wk from sowing (or 2–3 wk after transplanting to the bato buckets).

Continue to maintain these two leader stems on the plant. If one should weaken and an adjacent plant forms a vigorous side branch, it could be used to train it onto the neighboring support string to replace the weak stem of the other plant. Side shoots should be allowed to form one fruit. Once one fruit has set on a side shoot, cut the tip to stop it from growing further. This is similar to training the pepper side shoots.

Eggplants have very big flowers that easily release pollen (Figure 13.28). They must be pollinated similar to tomatoes. This can be done with bumblebees, or for small operations one can use a tomato "tickler" (Figure 13.29). Daily pollination is critical to good fruit set and high yields.

Eggplants yield very heavily initially and then their growth slows, as the fruit production draws heavily on their nutrients (Figure 13.30). Once fruit is removed, the plant will set more fruit above.

FIGURE 13.28 Receptive eggplant flower ready to pollinate. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

FIGURE 13.29 Pollination of eggplant using "Petal Tickler." (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

FIGURE 13.30 Initial heavy yields of eggplants. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

The eggplants will grow to about 12 ft (3.7 m) during a growing season. It is preferable, like peppers, not to lower them, as lowering shocks the plants. When lowering the plants, such as tomatoes, generally three leaves are removed weekly. This is not possible with eggplants, as they suffer too much by such a practice and will become stressed, resulting in small fruit. The best practice is not to lower the plants. The greenhouse at CuisinArt Golf Resort & Spa has sidewalls of 10 ft (3 m) to withstand hurricane winds of up to 150 mph (240 kph). For this reason, the eggplants must be lowered. This results in a reduction in fruit size. In this situation, it is better to use three crops annually. The old stems could be cut back to several side shoots formed at the base of the plant, and these new shoots allowed to replace the tall old stems (Figure 13.31) but production is not as good as with new plants.

Mini bush eggplants have also been grown in plant towers with a perlite substrate. Their cropping schedule is 3–4 mo (Figure 13.32).

13.5 COLUMN CULTURE

The growing of plants in vertical columns was developed in Europe, particularly in Italy and Spain. This system originated from the use of barrels or metal drums stacked vertically and filled with gravel or a peat mixture. Holes were punched in the sides around the containers in order to place the plants into the medium. Later, asbestos-cement pipes with spirally positioned holes were used.

FIGURE 13.31 Eggplant base shoots growing 8 d after cutting back. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

FIGURE 13.32 Mini eggplants in plant towers. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

FIGURE 13.33 Herbs in plant towers 1 mo after sowing (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

Watering and feeding was supplied by a trickle irrigation system mounted at the top of each column. If gravel was used as a medium, the nutrient solution could be recycled by placing the column over a collecting trough, which conducts the solution back to a centrally located reservoir.

A more recent development in column culture is the use of Styrofoam pots stacked vertically. Verti-Gro, Inc. of Florida developed this culture. The system was originally designed for growing strawberries, but it soon became evident that it could be used for herbs, spinach, lettuce, and other low-profile crops.

Styrofoam pots of dimensions 9 in. x 9 in. x 8 in. deep (23 cm x 23 cm x 21 cm) with slightly tapered sides are stacked one on the other by offsetting their orientation 45° (Figure 13.33).

They have special grooves on the topsides to fit the base of the pot above. The volume of each pot is 0.1 ft^3 (2.8 L). In general, 7–10 pots are stacked to form the tower. The number of pots depends on the crop to be grown and the available sunlight conditions. For herbs, every corner of each pot is sown, whereas for bush peppers or tomatoes, with a seven-pot plant tower, every other pot is planted with the ones between left empty to act as a spacer. A collection pot can be placed at the bottom of the plant tower to collect the leachate and pipe it to a drainpipe for re-circulation of the solution. If a pan or bucket filled with gravel to collect the drainage is used, a 0.75-in.-diameter tee with 4-in. (10-cm)-long piece of 0.75-in. pipe inserted in each opening of the tee forms a base of the standpipe, keeping the pots from shifting their position. This base is placed at the bottom of the pot or bucket filled with gravel (Figure 13.34). The Styrofoam pots have holes in the bottom for drainage to the one below. In addition, each pot has a 1-in.-diameter hole in the center for the pipe guide to pass. The conduit support pipe is passed into the top of the 4-in. (10-cm) riser from the tee after the conduit passes through a 3-in. x 3-in. x 0.2-in. (8 cm x 8 cm x 0.6-cm) thick swivel plate. The swivel

FIGURE 13.34 Filling of pots with coarse perlite. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

plate is a spacer between the two pieces of 0.75-in.-diameter sleeves supporting the plant tower pots. It allows the grower to rotate the towers easily for light orientation to the plants. This will produce more uniform growth by exposing the plants to an equal amount of sunlight. This is particularly important in the more northerly latitudes where sunlight casts shadows during the day.

When assembling the towers, the Styrofoam pots are slid over the conduit and 6.5-ft (2-m) plastic pipe sleeve. Fill the pots with a perlite-coco coir mix (85–15%) sequentially from the lower pot up, placing the next pot into the topside grooves once the lower pot is filled with substrate (Figure 13.34). Other substrates can be used, from coco coir alone to coarse perlite by itself, depending on the crops to be grown and local climatic conditions.

Finally, attach the conduit to an overhead support cable or galvanized pipe with galvanized tie wire. Alternatively, the conduit can be supported in the substrate below by first pounding in a larger diameter section, about 3 ft (1 m) in length and then slipping the smaller diameter pipe into it (Figure 13.35). One-inch tees placed at the top of each support pipe act as a guide for passing the black poly irrigation lateral (Figure 13.36). Then, attach the drip irrigation lines coming from the black polyethylene irrigation hose above the pot towers into the top pot and one at about halfway down the tower (Figure 13.36). The nutrient solution enters the pot on top and trickles down to the others below.

The collection bucket sits on top of a 1.5 in.-diameter drainpipe, which can return the solution to a cistern or conduct it away from the greenhouse to waste. Towers are spaced about 3 ft (90 cm) apart within rows, and rows are 4 ft (1.2 m) apart. Allow from 10 to 14 ft^2 (1.0-1.3 m^2) per tower. This is equivalent to 36 in. (0.9 m) within rows and 47 in. (1.2 m) between rows. Closer spacing is possible in more southern locations and with smaller crops as some herbs.

FIGURE 13.35 Placing base conduit support in soil.

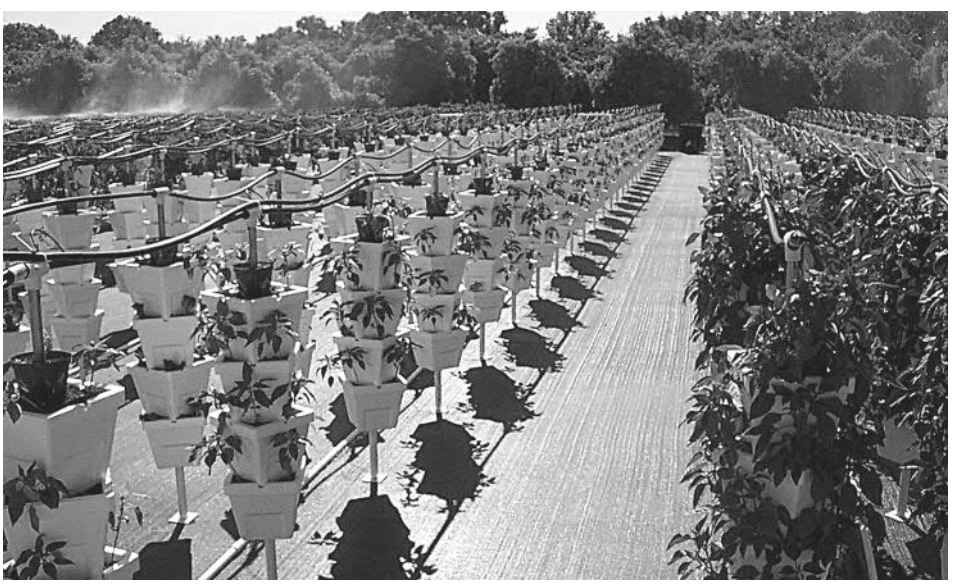

FIGURE 13.36 Plant towers in double rows outside with peppers. (From Verti-Gro, Inc., Summerfield, FL. With permission.)

Each plant tower will grow at least 40 strawberries, lettuce, or bok choy when using 10 pots per tower (Figure 13.37). Herbs that are sown in clumps will have many more plants per tower, but the same number of clumps. Plants are transplanted or sown directly into the corners of each pot. Many herbs may be seeded directly into the pots, but it is better to use transplants for lettuce, bok choy, and of course strawberries to save time.

FIGURE 13.37 Plant towers of bok choy. Note: The tower in front is 44 d from sowing, usually ready to harvest at 50 d. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

The pot column system is capable of producing six to eight times as much per unit area as equivalent field crops and three to four times as much as greenhouse bench crops. The plant density for lettuce, spinach, herbs, and strawberries is about three plants per square foot (32-plants per square meter) or 131,000 plants per acre (320,000 plants per hectare). One column of strawberry plants should produce between 10 and 13 pt of fruit per month. One acre (3,200 towers) (8,000 towers per hectare) should produce from 23,000 to 35,000 lb (10,500–15,700 kg) of strawberries monthly, which is equivalent to 31,500–41,000 pt. One acre of field crop having 17,500 plants produces from 4,000 to 6,000 pt/mo. Column culture grows about eight times as many plants in the same area as field cultivation.

In 1997, the author presented a paper on this type of column culture at the International Conference of Commercial Hydroponics at the Universidad Nacional Agraria La Molina, Lima, Peru (Resh, 1997). Interest in this column culture led to the development of a commercial installation at Cieneguilla, northeast of Lima, by Productos Hidroponicos ACSA. They worked with Mr. Alfredo Delfin of the Center of Hydroponic and Mineral Nutrition Investigation at the university to develop a similar Styrofoam pot tower to Verti-Gro (Figure 13.38) (Rodriguez Delfin, 1999). Their 4,000- m^2 (1-acre) facility had 3,000 pot columns with 10 pots per tower. With 40 strawberry plants per tower they grew a total of 120,000 plants. Four sectors were irrigated twice a day for 20 min per cycle. The substrate was composed of pumice and peat. Production varied from 125 to 600 kg (275–1,320 lb) daily during winter and summer seasons, respectively. The objective was to produce 500 g of fruit per plant. The university also experimented with the traditional sack culture of strawberries for tropical conditions.

FIGURE 13.38 Strawberries in plant towers in Peru.

13.6 SACK CULTURE

Sack culture is a simplification of column culture (Linardakis and Manios, 1991). The system is basically the same except that polyethylene "sacks" are used instead of rigid drums, pipes, or pots. Black layflat 0.15-mm-thick polyethylene of about 6 in. (15 cm) diameter and 6 ft (2.0 m) length is filled with a peat-vermiculite mixture or any other substrate such as a coco coir mix. The bottom end is tied to prevent the medium from falling through, and the top end is tied to constrain the medium into a sausage-like form. The top end is tied by a wire or rope to the greenhouse, and the sack hangs down, giving a column effect.

Watering and feeding is automated by use of a trickle drip line system to each sack from a central nutrient reservoir or fertilizer injector. Small holes 2.5–5 cm (1–2 in.) in diameter are cut around the sack's periphery, into which plants are placed (Figure 13.39). The nutrient solution is applied at the top end of the sack and percolated down through the entire sack.

The sacks, supported by the greenhouse superstructure or other supports, are spaced 80 cm (32 in.) apart within the rows, and the rows are spaced at 1.2 m (about 4 ft).

Watering and feeding cycles are generally from 2 to 5 min, giving a volume of 1–2 L of nutrient solution per sack per irrigation cycle. The number of cycles per day depends on the plant stage of growth and weather conditions. Nutrients are not recycled but allowed to percolate from the top to

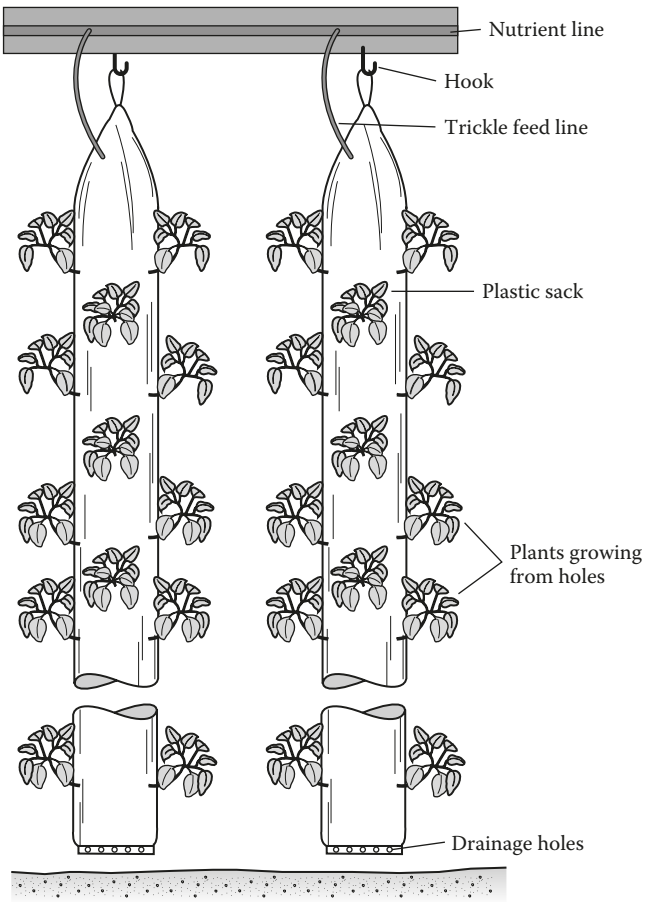

FIGURE 13.39 Schematic of hanging sack culture system. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

the bottom of the sack and out the drainage holes. At the end of each growing period, the entire sack and substrate is disposed of and new ones are made up with sterile medium.

This system is particularly useful for lettuce, herbs, strawberries, and other low-profile plants, which normally require a lot of greenhouse floor area with little utilization of the vertical space. However, tests with bush varieties of tomatoes, peppers, eggplant, cucumbers, and other vegetables had been successful experimentally (Tropea, 1976).

A company, in Bogota, Colombia, FRESEX, has been growing 8 ha (20 acres) of strawberries in sack culture from the late 1990s. The farm is located near Bogota at high elevation in an area of conventional field-grown strawberries. Field production of strawberries encounters many disease problems, resulting in reduced yields. For this reason, the company turned to an alternative method using a hydroponic system of sack culture. In 1997 the farm had 30,000 sacks with 28–30 plants each, giving a total of 800,000 plants.

With the tropical climate of the region, greenhouses are unnecessary. Simple systems of wooden posts and cross members support the sacks. The sacks are filled with a medium of 75% rice hulls and 25% coal ash (scoria). The 15 cm (6 in.) diameter by 2 m (79 in.) long sacks of 8-mil thickness are tied to the wooden cross members (Figure 13.40). Spacing is 0.8 m (31.5 in.) within rows and 2 m

FIGURE 13.40 Support of strawberries in sack culture in Colombia. (From Fresex, Bogota, Colombia. With permission.)

(6.5 ft) between rows. The sacks are tied into seven sections, each to prevent settling of the medium and resultant compaction (Figure 13.41). Four plants are set into each section to give at least 28 plants per sack. Drainage is through 10 holes punched in the lower heat-sealed end of the sacks. The leachate flows from the base of the sacks into a drainage ditch below, which takes the spent solution to waste (Figure 13.42). It is not recirculated.

A drip irrigation system distributes the nutrient solution to the sacks from a large central cistern. Two 0.5-in.-diameter black polyethylene laterals run along the wooden cross members from a PVC main. Drip lines enter the sacks at four sections (Figure 13.43) going down and around the sacks. About three to six irrigation cycles per day provide from 3 to 6 L (3–6 qt) per sack depending on weather conditions and crop maturity.

The most widely used varieties of strawberries are "Chandler" and "Sweet Charlie," which are purchased from California as small plants. Yields range from 500 to 900 g (1–2 lb) per plant over a 7-mo cropping period (Figure 13.44). The objective is to produce from 800 to 900 g per plant. The company exports strawberries to North America, Europe, and the Caribbean, with strongest sales from November through January. With the low capital cost of installing an outdoor sack culture system, the return on investment should be attractive.

13.7 STERILIZATION OF THE MEDIUM

All the media mentioned in this chapter must be either changed between crops or sterilized as outlined in Chapter 4.

13.8 ADVANTAGES AND DISADVANTAGES OF PEAT AND COCO COIR MIXTURES

The advantages of peat and coco coir mixtures are as follows:

1. Similar to sand and sawdust cultures, they are open systems; therefore, there is less spread of diseases such as *Fusarium* and *Verticillium* wilts, especially in tomatoes.

FIGURE 13.41 Sacks are tied into seven sections. (From Fresex, Bogota, Colombia. With permission.)

FIGURE 13.42 Drainage at base of sack. (From Fresex, Bogota, Colombia. With permission.)

FIGURE 13.43 Drip irrigation system to sacks. (From Fresex, Bogota, Colombia. With permission.)

2. The problem of plugging drainage pipes with roots does not occur.
3. There is good lateral movement of nutrient solution throughout the root zone.
4. There is good root aeration.
5. A new nutrient solution is added during each irrigation cycle.
6. The system is simple and easy to maintain and repair.
7. The high water-holding capacity of the medium reduces risk of water stress should a pump fail.
8. It is adaptable to fertilizer injectors, and therefore less space is required for storage tanks.
9. Peat, perlite, and vermiculite are generally readily available in most regions of the world. This is also true for coco coir, and in addition coco coir is a "sustainable" substrate.
10. Sack culture enables a greenhouse operator to efficiently utilize vertical space for crops such as lettuce and strawberries, which normally use a large amount of floor area. Therefore, a much greater number of plants can be grown in a given area of greenhouse.
11. Sack and column cultures keep plant parts and fruit off the underlying medium, thus reducing disease problems of fruit and vegetation.

The disadvantages of peat and coco coir mixtures are as follows:

1. The medium must be sterilized between crops by steam or chemically, which requires more time than in gravel culture. However, sterilization is very thorough.

FIGURE 13.44 High strawberry yields in sack culture in Colombia. (From Fresex, Bogota, Colombia. With permission.)

2. Over the cropping season, salt accumulation can build up in the medium to toxic levels. Proper and regular leaching (at least 25%) with each irrigation cycle will overcome this problem.
3. Plugging of drip feed lines may occur if proper filters are not used or if cleaning of these filters is neglected.
4. Since peat is organic in nature, it decomposes over time with continual cropping. Between crops it should be cultivated and additional peat must be added. Coco coir does not decompose as readily as peat.
5. Perlite, pumice, and vermiculite break down with continued use, resulting in compaction of the medium. For this reason, the peat mixtures are generally replaced between crops, resulting in replacement costs (of both medium and labor) each year.
6. If compaction occurs during the cropping period, root aeration will be greatly restricted, resulting in poor crop yields. Both the original mixture ratios and handling are important to prevent compaction.

In summary, peat mixtures are used extensively in contain-grown plants. In beds, sand, rice hulls, coco coir, or sawdust would be more suitable. In sack culture, peat, rice hulls, coco coir, or sawdust are most suitable because of their light weight. Of these cultures, perlite bags and coco coir slabs offer the most potential for future commercial production of vine crops.

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14 Vertical Indoor Farming

14.1 INTRODUCTION

Indoor vertical farming, also termed Vertical Farms (VF), was developed some time ago, but without the promotion that they are now receiving. A vertical greenhouse farm was introduced at a Soilless Culture Conference in the Canary Islands in 1976. Othmar Ruthner of Vienna, Austria had built a vertical conveyor belt system of plant trays in a vertical greenhouse (Figures 14.1 and 14.2). While the system functioned to grow low-profile plants, the complicated mechanics resulted in high maintenance. Another approach was the column and sack culture systems developed about the same time in Spain and Italy. Black polyethylene sacks of medium fed a nutrient solution by drip irrigation may be supported by a greenhouse structure (Figure 14.3). This was a hydroponic or soilless system for growing strawberries, lettuce, and herbs. The project was about 8 ha (20 acres). These vertical growing systems had only short-term success due to economics and logistics of their operation. The sacks often tore in addition to requiring a lot of labor to fill new sacks for each crop cycle making the system very labor intensive. As described in Chapter 13, FRESEX, near Bogota, Colombia, uses sack culture to grow strawberries.

14.2 VERTICAL GROWING SYSTEMS

There are vertical hydroponic cultural systems proven to be feasible in greenhouse and outdoor growing conditions. They include column culture in the form of plant towers as described in Chapter 13. They are most suitable for growing strawberries and herbs. Verti-Gro (www.vertigro.com), was the first company to apply this culture on a commercial scale using stacking of Styrofoam pots to form a plant tower. These plant towers were used successfully at the hydroponic farm of CuisinArt Golf Resort & Spa in Anguilla, B.W.I. The Verti-Gro plant towers increase production of low-profile plants, such as strawberries, herbs, and bok choy over bed and table systems.

There are a number of commercial greenhouses using various forms of plant towers. Micro Farm in Indiana, developed their "Verti Tube" system using 8-in. diameter PVC pipes 12 ft tall. There are removable cups in the pipes that hold the plants, which are started in foam growing cubes. Irrigation is by an aeroponic misting system within the tubes. Products grown include leafy greens, lettuce, kale, and pak choi. They presently have 4,000 ft^2 of Verti Tubes.

Eden Green Technology of Dallas, Texas has a 40,000 ft^2 greenhouse with a specific design of vertical plant towers (www.edengreen.com) (Figures 14.4 and 14.5). They also construct modular greenhouses of 1.5 acres (0.6 ha) as turn-key operations, offering management and technology training to clients. They grow leafy greens, lettuce, bok choy, and chard.

While these plant towers are a form of vertical growing systems they are not considered vertical farms (VF). Today vertical farms include vertical greenhouses and indoor (warehouse) vertical growing. The emphasis is on establishing these vertical farms in or very close to cities, hence the name *urban vertical farms.*

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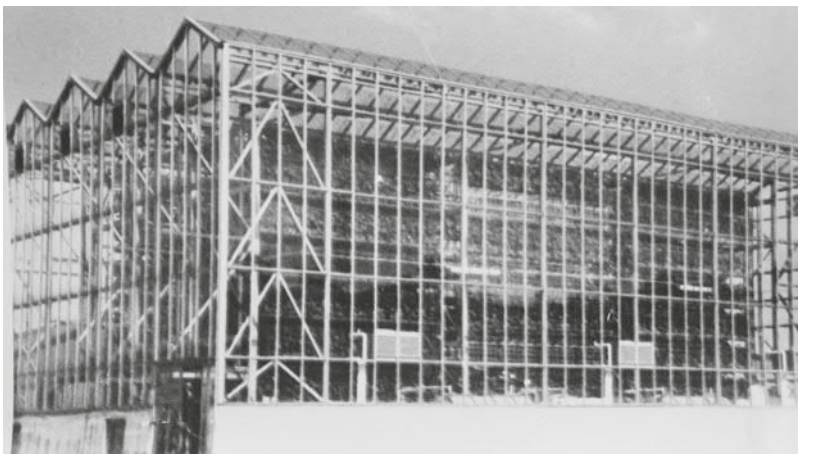

FIGURE 14.1 Othmar Ruthner vertical greenhouse, Vienna, Austria

14.3 AUTOMATED VERTICAL HYDROPONIC SYSTEMS

Over the past few decades, hydroponic enthusiasts have designed systems to increase production within a given area. Most are automated vertical production systems that rotate while passing a light source in closed insulated buildings or in greenhouses.

Valcent Products (EU) Limited (www.valcent.eu) is testing an automated vertical hydroponic system at Paignton Zoo in Cornwall, United Kingdom (Bayley et al., 2011). Their vertical system is trademarked as "VertiCrop." They started trials in 2008 growing leafy crops for zoo animals. Kevin Frediani (2010a, 2010b, 2011a, 2011b), the curator of plants and gardens at Paignton Zoo, oversees the research on the VertiCrop growing system. He works with the animal nutritionists to select the right types of crops most suitable for the animals. They feed the animals the total plants including roots, as that decreases waste while increasing fiber to the animals. The growing of their own leafy crops makes it possible to provide the animals with nutritious crops without concern for weather or season availability as they are grown in a greenhouse on-site.

The VertiCrop system is a closed-loop conveyor system suspended by an overhead track that carries 70 hangers that hold eight pairs of growing trays contained in plastic trays (Figure 14.6). There are eight levels stacked 3 m high. The trays are designed for growing microgreens, lettuce, and salad mixes. They are working on LED lighting for the conveyor system to pass in its rotation. The system is automatically irrigated from a central feeding/injection system (Figure 14.7). All leachate is captured, filtered, and recycled through the irrigation system (Figure 14.8). The nutrient solution enters at one side of the system as the trays travel past nozzles located at a centralized irrigation station (Figure 14.9).

Frediani (2010b) claims that in approximately 100 m^2 (1,076 ft^2) of area 11,200 plants can be grown at any one time. Use of the greenhouse floor area is increased by the conveyor system curving back and forth in a serpentine fashion (Figure 14.10). He further states that up to 250 lettuces per square meter (10.76 ft^2) can be obtained with a 6-m (19.69 ft) high unit and says that it is about 50 times greater than under field growing. This type of growing has potential use in urban food production. Such a system would fit well into the concept of rooftop gardening discussed earlier, as it would increase production within a unit area.

A specialized machine has been constructed to remove the trays when harvesting and replacing them during transplanting to reduce manual labor. Plants are started in growing cubes and transplanted to mesh pots, which are then placed in the trays of the conveyor system (Figure 14.11).

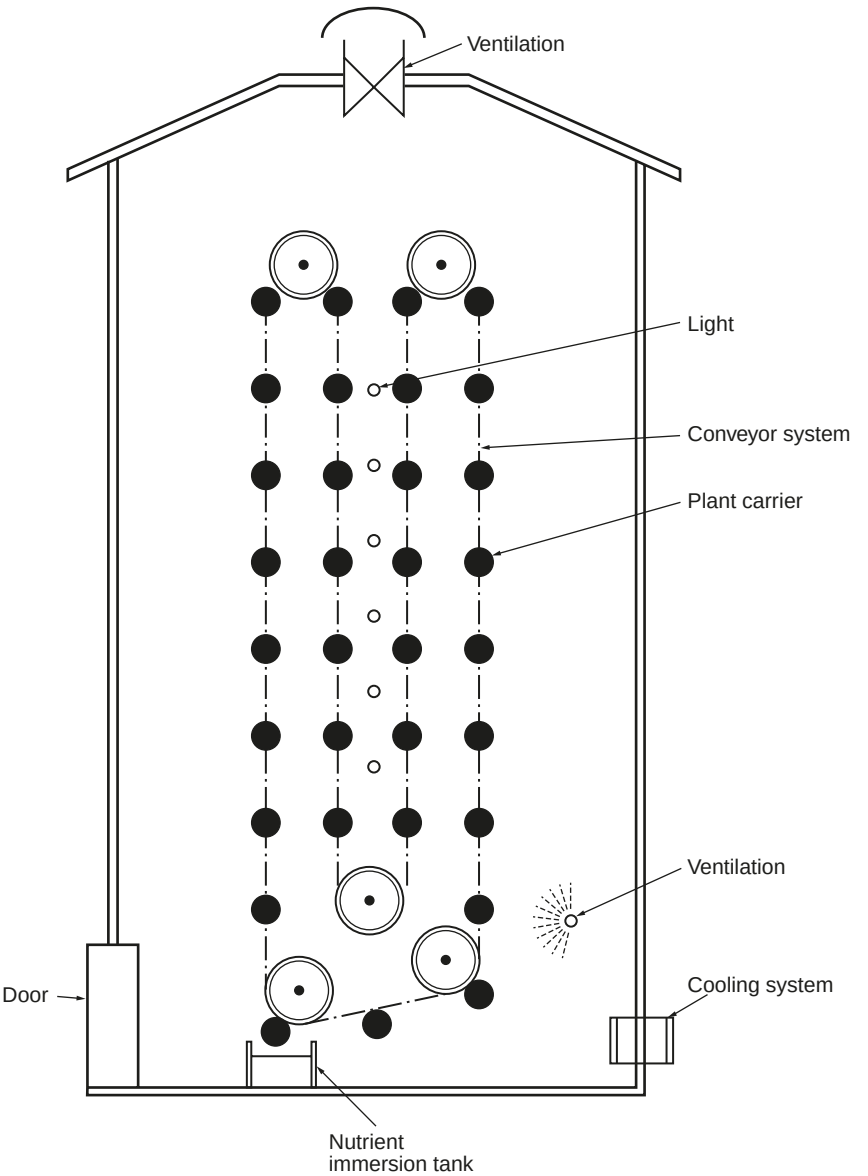

FIGURE 14.2 Conveyor growing system of vertical greenhouse. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

14.4 VERTICAL GREENHOUSES

Little work was done after 1976 on the development of vertical greenhouses until Dr. Dickson Despommier, a professor of microbiology at Columbia University in New York, started researching raising crops in tall buildings with some architectural students in 1999. He developed this concept for 10 yr before writing an article on growing crops in high-rise buildings that was published in the 2009 issue of *Scientific American*. In 2010 he published his widely received book, *The Vertical Farm: Feeding the World in the 21st Century*. This publication caught the attention of many

FIGURE 14.3 Early sack culture in Italian greenhouse.

FIGURE 14.4 Eden Green Technology vertical plant towers with oakleaf lettuce. (From Eden Green Technology, Dallas, TX. With permission.)

entrepreneurs thinking of a profitable business in urban vertical farms. Many conceptual designs appeared in articles on numerous websites (Figures 14.12 and 14.13).

There are many vertical greenhouse concepts by architects of actual high-rise buildings within cities. Some of the concepts are presented in an article, "11 Vertical Farms to Transform Our

FIGURE 14.5 Eden Green Technology vertical plant towers of chard and bok choy. (From Eden Green Technology, Dallas, TX. With permission.)

FIGURE 14.6 Vertical automated growing system. (From Valcent Products [EU] Ltd., Cornwall, UK. With permission.)

Cities." This is a report by Brian Clark Howard in 2010 in the magazine *Esquire*: (www.esquire.com/news-politics/g545/vertical-farms). While these concepts are fascinating, they are far from being a practical solution to produce vegetable crops due to economics and logistics of crop production.

FIGURE 14.7 Priva injection system. (From Valcent Products [EU] Ltd., Cornwall, UK. With permission.)

FIGURE 14.8 The drain lines at the back of the trays. (From Valcent Products [EU] Ltd., Cornwall, UK. With permission.)

A few vertical greenhouse projects have been developed in the U.S. and Singapore. These include "Vertical Harvest Farms" in Jackson, Wyoming (www.verticalharvestjackson.com) (Figure 14.14) with expansion plans in Westbrook, Maine and future projects in Chicago and Philadelphia. Similarly, "Sky Greens" in Singapore (www.skygreens.com) (Figure 14.17) has a vertical greenhouse. The design of these systems is based on the Ruthner vertical greenhouse using vertical and horizontal chain growing systems (Figures 14.15 and 14.16). Vertical Harvest Farms is a three-storey

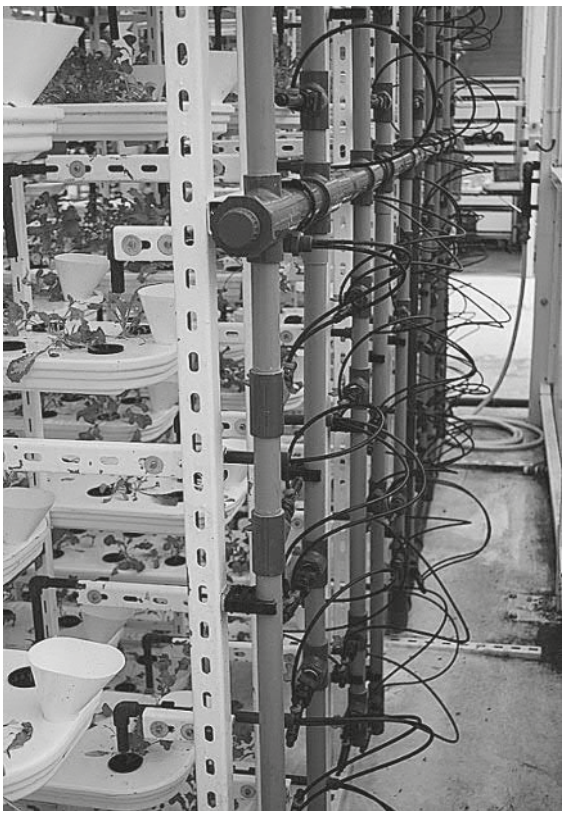

FIGURE 14.9 Irrigation header above passing trays. (From Valcent Products [EU] Ltd., Cornwall, UK. With permission.)

greenhouse on a 4,500 ft^2 (418 m^2) area adjacent to a parking building. It was constructed at a cost of almost $4 million. The total greenhouse area is 13,500 ft^2 (1,254 m^2). The greenhouse is attached to one side of the parking building. The facility is fully equipped with LED lighting. They grow microgreens, lettuce, leafy greens, and cherry tomatoes. Their market is to local restaurants, supermarkets, specialty grocers, and direct to consumers in the town of Jackson and the greater Teton County.

Sky Greens in Singapore is an independent vertical greenhouse structure using a chain driven vertically rotating series of growing trays mounted on an A-shape aluminum frame (Figures 14.18 through 14.20). Each frame is 9 m tall with 38 tiers of growing troughs that rotate around so the plants receive uniform sunlight. Similar to almost all vertical growing systems low-profile crops of various Asian leafy greens, bok choy, and lettuce are grown. This commercial operation began in 2012 and continues to the present. Despommier (2018) claims there are a total of six vertical farms in Singapore, of which Sky Greens is the largest.

14.5 VERTICAL INDOOR FARMS

Over the next few years prototypes of vertical farms were developed in South Korea, over 50 plant factories in Japan, a commercial vertical farm in Singapore, plant factories in China and North America. Information of growing crops in vertical farms is presented in a number of articles (Despommier, 2010, 2015; Michael, 2017a, 2017b; Podmerzig, 2016).

FIGURE 14.10 VertiCrop system where overhead conveyor curves back to change direction. (From Valcent Products [EU] Ltd., Cornwall, UK. With permission.)

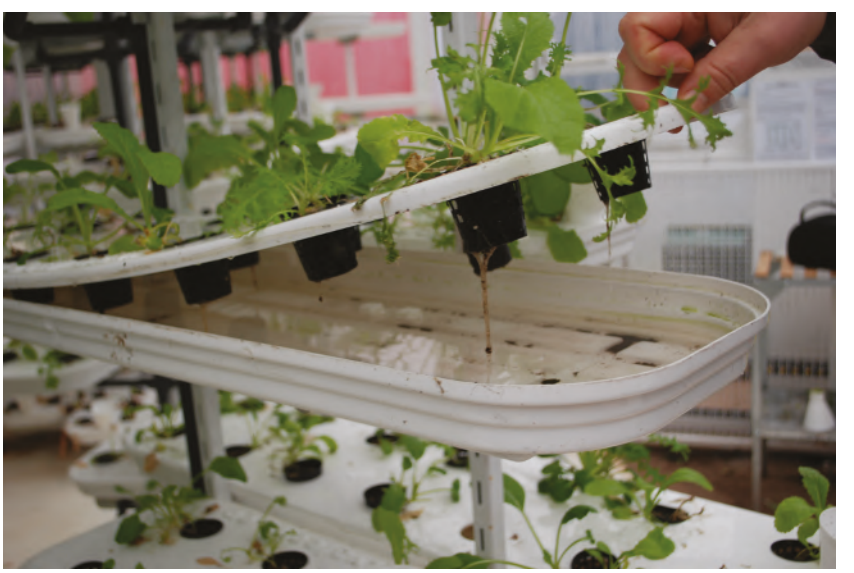

FIGURE 14.11 Plants in mesh pots. (From Valcent Products [EU] Ltd., Cornwall, UK. With permission.)

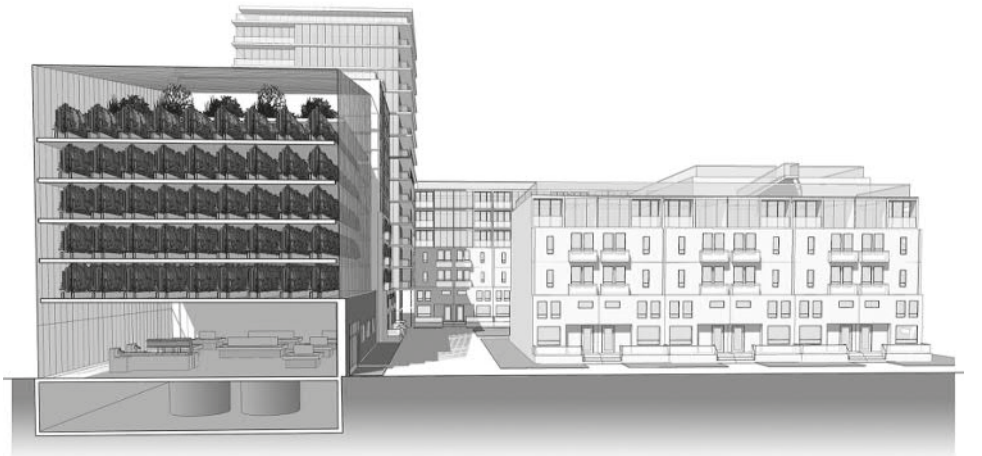

FIGURE 14.12 Conceptual design of a hydroponic farm attached to office buildings and/or residences. (From Gordon Graff, Agro-Arcology, Toronto, Canada. With permission.)

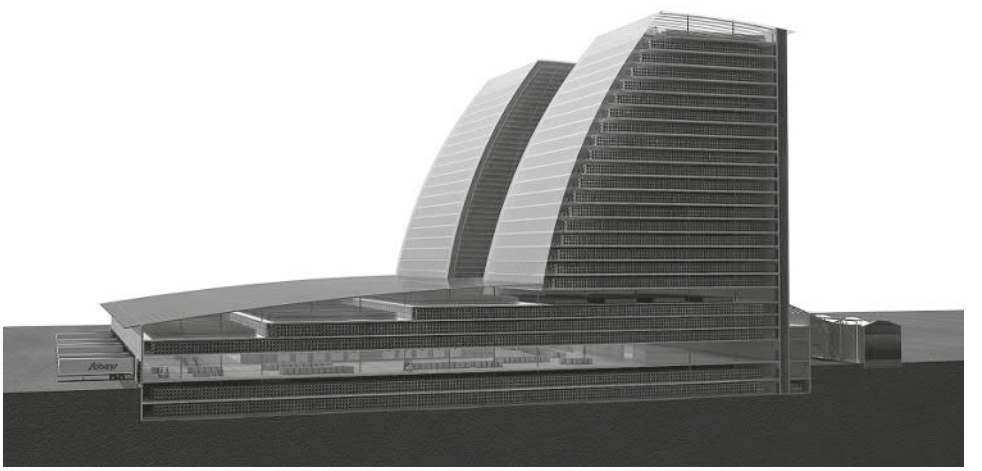

FIGURE 14.13 A conceptual design of a vertical greenhouse. (From Gordon Graff, Agro-Arcology, Toronto, Canada. With permission.)

Despommier (2018) in his report, "Status of Vertical Farms 2018" posted on his blog December 2018, states that in response to the earthquake and tsunami in Japan in 2011, Chiba University with collaboration from Toshiba, Panasonic, Fujitsu, Mitsubishi, and Toyota, formed several vertical farm (VF) companies to retrofit abandoned warehouses with growing systems to produce leafy green vegetables. He said that several hundred VFs are now operating in Japanese cities.

Kozai et al., (2016) state there are over 56 commercial VFs in Taiwan. YesHealth Group of Taiwan grows fruits and vegetables in a 14-storey VF using LED lighting. In 2018, they were reportedly investing US$25 million in a vertical farm pilot factory at the National Agri-Food Innovation

FIGURE 14.14 Vertical greenhouse next to parking building. (From Vertical Harvest Farms, Jackson, WY. With permission.)

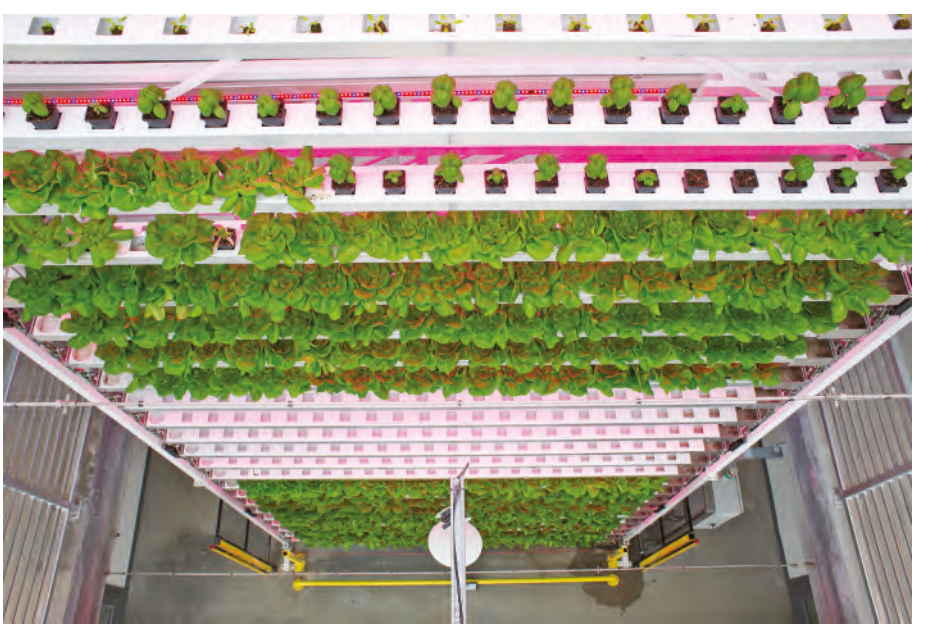

FIGURE 14.15 Vertical rotating chain system with lettuce. (From Vertical Harvest Farms, Jackson, WY. With permission.)

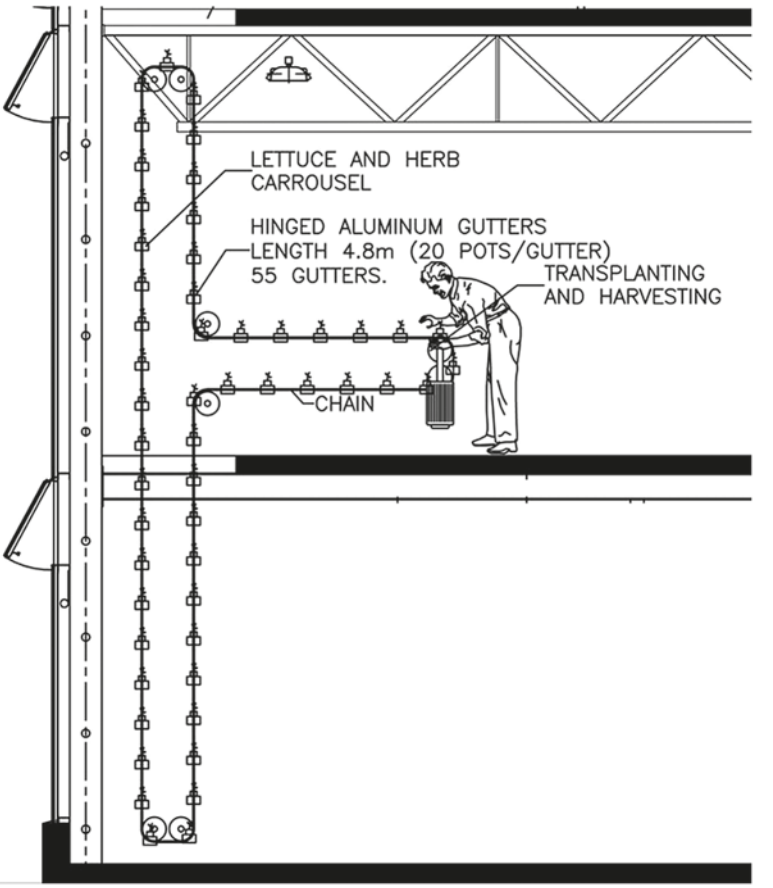

FIGURE 14.16 Sketch of moving chain system of Vertical Harvest Farms. (From Vertical Harvest, Jackson, WY. With permission.)

Campus in York, United Kingdom. They partnered in a large VF with Yuankang iFarm, Shenzhen, China. In a partnership with Nordic Harvest of Copenhagen, Denmark, they finished the first phase of construction of a 14-storey VF in a 7,000 m^2 (75,320 ft^2) facility in 2020. Production is scheduled to begin in the first quarter of 2021(www.yeshealthgroup.com).

China has numerous VFs, but no information is available on them with the exception of Sanan Sino-Science, which has constructed a VF with a one hectare footprint. It employs LED grow lights.

In 2010, the Chicago Metropolitan Area became a center for VF startups due to a large market of consumers seeking locally grown produce. "Farm Here" was an early startup that used a combination of aquaculture and aeroponics to raise tilapia and grow leafy greens. "The Plant" was another VF operation that occupied an abandoned stockyard warehouse. The three-story building was renovated and hydroponic growing systems were installed with different crops growing at each floor.

In 2012, "Green Sense Farms" built the largest commercial indoor VF at the time, in Portage, Indiana (www.greensensefarms.com). The 20,000 ft^2 (1,858 m^2) farm was constructed in a commercial warehouse (Figure 14.21). "Green Sense Farms" grew lettuce, baby greens, herbs, and microgreens with a proprietary hydroponic system, operated by a computer-driven platform with sensors and automated controls for two large climate-controlled grow rooms. The operation included 5,000 LED lights and 10 to 13 tiers of growing shelves per tower. The foregoing information was provided by Robert Colangelo, founder of "Green Sense Farms" (Figure 14.22).

FIGURE 14.17 Sky Greens vertical greenhouse in Singapore. (From Sky Greens, Singapore. With permission.)

The farm was converted into a large-scale commercial research facility in 2018 to provide contract research, farm design, and build services.

Green Spirit Farms in New Buffalo, Michigan was a small-scale VF that grew leafy greens for local restaurants in the New Buffalo area. Buckeye Fresh (www.buckeyefresh.com) in Medina, Ohio with 30,000 ft^2 (2,788 m^2) of production area grows kale, basil, and lettuce blends.

There are about 40 vertical farms in the United States. These are all in large warehouses. Most use a vertical configuration of shelving, while some use shipping containers. Shipping containers are discussed later as a special form of vertical farming. Vertical farms are those using multi-levels of shelving or other stackable growing systems within a large warehouse.

The leaders in vertical urban farming having large, highly technical growing operations in large warehouses include AeroFarms in New Jersey (www.aerofarms.com), Bowery Farming Inc. (www.boweryfarming.com) in New York, and Plenty in San Francisco (www.plenty.ag). All of these urban vertical farms grow leafy greens, lettuce, and some herbs.

AeroFarms started production in 2016 in a 70,000 ft^2 (6,500 m^2) warehouse of an abandoned steel mill in Newark, New Jersey. They claim to be able to harvest 2 million pounds of leafy greens annually with their vertical tier system of aeroponic culture. The 30-ft (9 m) high shelf system is 12 tiers, each equipped with LED lights (Figures 14.23 and 14.24). The cost of the project was $39 million. The technology of AeroFarms is a patent design of trays supporting a cloth (capillary mat) growing medium (Figure 14.25). Underneath in the solution chamber is a series of mist nozzles providing the nutrient solution to the suspended roots of the plants. The growing medium is a "cloth" made from recycled plastic. The entire 16-day growing cycle of leaf greens from seeding through harvest takes place on this reusable "cloth" medium.

Bowery Farming is the largest indoor farming company in the United States, with two large-scale commercial farms in operation in Kearny, New Jersey and Nottingham, Maryland (outside of

FIGURE 14.18 Vertical chain system of Sky Greens growing bok choy. (From Sky Greens, Singapore. With permission.)

Baltimore) and recently announced its newest, most technologically advanced farm in Bethlehem, Pennsylvania. The company has more than $172.5 million in investment funding. The company sells produce to almost 700 grocery stores and offers e-commerce platforms serving the Tri-state and Mid-Atlantic regions. Their long-term objective is to build smart indoor farms near major cities in the United States and worldwide.

Bowery's farms integrate automation into their system of grow trays, which are stacked vertically in shelves within large industrial spaces (Figure 14.26). With sensors and cameras within the farm, all stages of plant growing are monitored from seeding to harvesting. In addition to monitoring plant health, this automation system creates optimum growing conditions for the crop. Bowery states, "Our magic is the convergence of hardware and software to autonomously create precise farming conditions."

The process of growing starts with seeding into trays of a growing medium with an automated seeder (Figure 14.27). The seeded flats move to a germination chamber providing optimum temperatures and moisture levels for germination to occur over several days. From there an automated conveyor belt moves the trays into a grow room. The movement of the trays into the growing system to replace trays moving out for harvesting is operated by their "BoweryOS" operating system. In the grow room of tiered shelves the crop is monitored with the sensors and cameras that feedback information to the BoweryOS that controls the growing parameters for the crop from lighting to irrigation schedules (Figure 14.28). The BoweryOS detects when crops are ready to harvest and initiates movement of those trays from the grow room to the harvesting-packaging station (Figure 14.29).

FIGURE 14.19 Vertical A-Frames of moveable chain system. (From Sky Greens, Singapore. With permission.)

Bowery sells 13 different products, including romaine, crispy leaf, and butterhead, bok choy, kale, arugula, basil, herbs, and more.

In 2021, Bowery opened its second R&D facility in Kearny, New Jersey, which is a multidisciplinary innovation center for plant science, product development, and technological advancements specifically for vertical farming.

Urban vertical farms are planned for many large cities around the world.

ZipGrow™ is a specific patent growing system of vertically oriented gutters called "ZipGrow™" towers (www.zipgrow.ca) (Figure 14.30). Seeds are sown in "FlexiPlugs" consisting of a peat and a foam binder. In VFs using aeroponics or the raft culture system, seeds can be sown in "FlexiTrays," which are the FlexiPlugs pre-filled in a ready-to-use propagation tray. This facilitates automation of the seeding and transplanting stages. These products are available from "Quick Plug" (www.na.quickplug.global/products-stabilized-growing-media). The trays are placed in an ebb-and-flow vertically stacked rack system with a reservoir and pump for re-circulation of the water/nutrient solution during germination and subsequent seedling growth. LED lights are located above each tier of trays.

Commercial growing towers are 8 ft tall mounted on Z-frames having wheels termed "ZipRacks™" (Figure 14.30). The wheels allow the racks to be moved around the growing space. All plumbing is connected with quick-connect fittings. The nutrient solution comes from a reservoir

FIGURE 14.20 Interior view of vertical A-Frames of moveable chain system. (From Sky Greens, Singapore. With permission.)

that automatically balances nutrient and pH levels to set values, and enters the top of each grow tower via a drip irrigation system (Figure 14.31). The solution drains to the bottom of the tray and enters a collection gutter where it is conducted back to the nutrient tank. The nutrient solution is distributed down the tray (channel) by use of a "Matrix Media™" (Figure 14.32). This comes in length the same as the growing channel. Since the system is not an aeroponic one with mist nozzles down the channel, but a simple drip irrigation system with an emitter at the top of each tray, the solution must be distributed down the channel to contact the plant roots. Sandwiched in between the Matrix Media™ is a felt strip called a "Wicking Strip" that is in contact with the grow plugs, and ensures an equal amount of water and nutrients are delivered to each plant in the tower.

The Matrix Media™ is the growing medium distributing the nutrient solution and supporting the plants within the tower. The Matrix Media™ fills the entire channel space. This medium is of fibrous nature and can be reused indefinitely with proper care and cleaning. The use of such a medium means that the seedlings must be transplanted by hand into the medium while spreading the slit side apart. A special hook is used to pull the medium into the tray as the seedlings are transplanted. This work must be done on a table with the towers sitting horizontally. The transplanted towers must then be lifted and placed onto the ZipRack™ support growing structure. Automation of this process is not available except for the movement of the ZipRacks™ to the packing area where the crop can be harvested. Rack mobility combined with grow tower mobility means that all planting, harvesting,

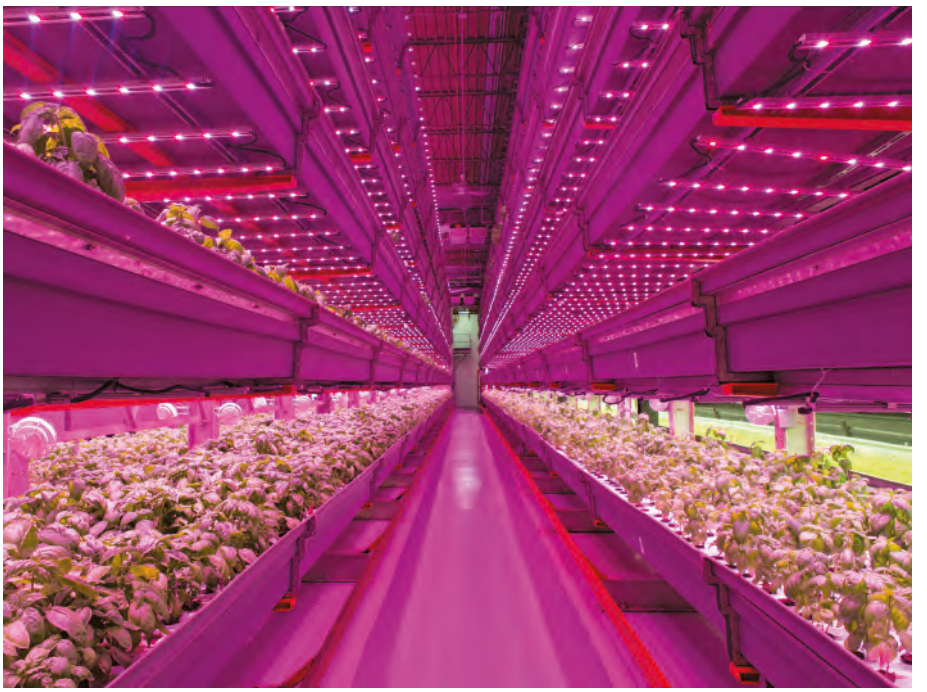

FIGURE 14.21 Green Sense vertical indoor farm growing basil. (From Green Sense Farms, Portage, Indiana. With permission.)

FIGURE 14.22 Green Sense founder Robert Colangelo showcasing young butterhead lettuce plants. (From Green Sense Farms, Portage, Indiana. With permission.)

FIGURE 14.23 AeroFarms 12-tier vertical farm with LED lights. (From AeroFarms, Newark, New Jersey. With permission.)

FIGURE 14.24 AeroFarms 12-tier vertical farm with LED lights showing arrangement of trays. (From AeroFarms, Newark, New Jersey. With permission.)

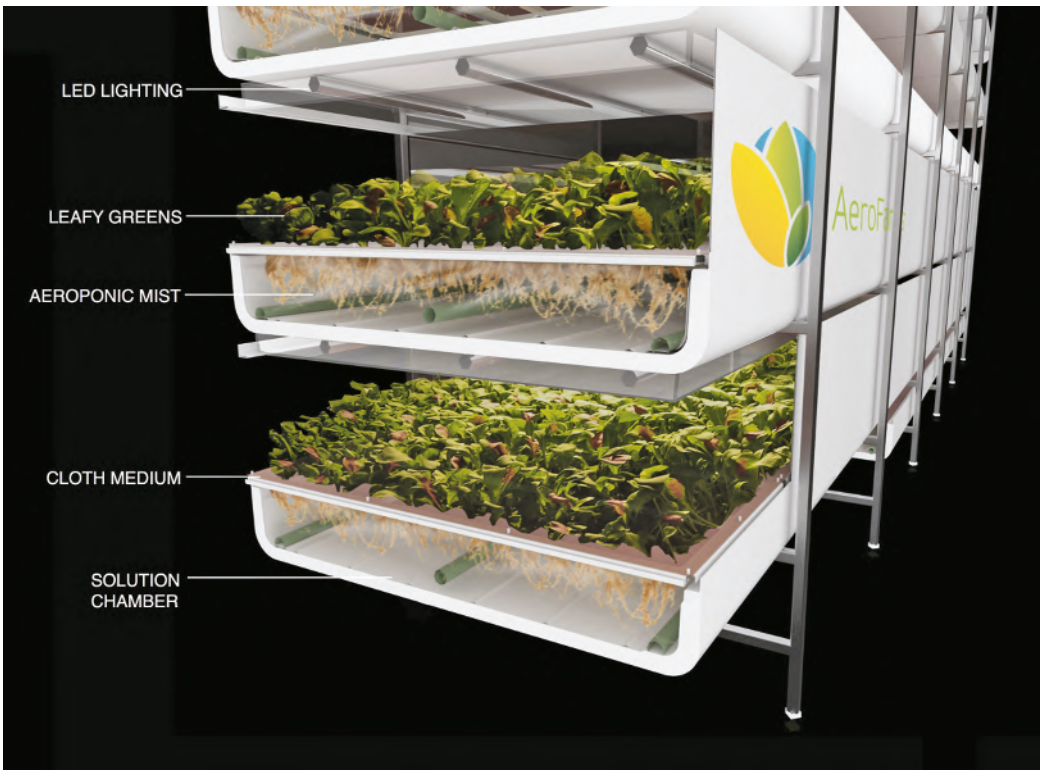

FIGURE 14.25 AeroFarms aeroponic growing system. (From AeroFarms, Newark, New Jersey. With permission.)

FIGURE 14.26 Bowery Farming moveable raft culture system vertical farm. (From Bowery Farming, New Jersey. With permission.)

FIGURE 14.27 Automated seeding of trays with substrate. (From Bowery Farming, New Jersey. With permission.)

FIGURE 14.28 Bowery Farming crop of bok choy under LED lights. (From Bowery Farming, New Jersey. With permission.)

FIGURE 14.29 Bowery Farming moveable rafts with Bibb lettuce on way to packing facility. (From Bowery Farming, New Jersey. With permission.)

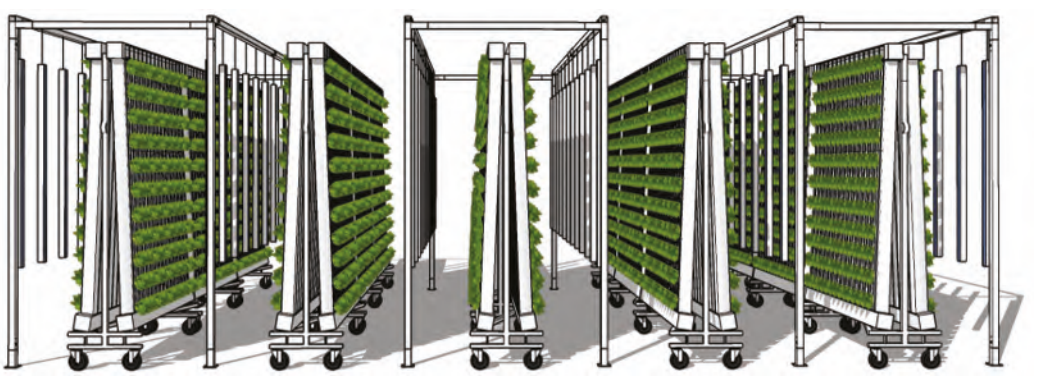

FIGURE 14.30 Layout of ZipGrow™ tower vertical system. (From ZipGrow™, Cornwall, Ontario, Canada. With permission.)

and cleaning operations can be done with ease without special equipment (that is scissor-lifts) to reach crops planted at higher elevations

LED lights are mounted vertically on moveable racks or on an overhead support frame (Figure 14.33). These are located between each ZipRack™ of plants. This ZipGrow™ system is suitable only for low-profile crops like leafy greens, herbs, microgreens, and lettuce (Figure 14.34).

FIGURE 14.31 Drip irrigation enters the top of the ZipGrow™ tower with Matrix Media™. (From ZipGrow™, Cornwall, Ontario, Canada. With permission.)

FIGURE 14.32 Matrix Media™ inside grow tower. (From ZipGrow™, Cornwall, Ontario, Canada. With permission.)

Plenty, Inc. has a farm in San Francisco, a research farm in Wyoming and is building a large indoor farm in Compton, California, using a vertical gutter system of growing in large warehouses. The San Francisco farm is 100,000 ft^2, including office space and grow rooms. They make similar claims to the others in the industry that the VF can get 350 times the produce out of a given acre of

FIGURE 14.33 Lights are mounted vertically beside the moveable racks. Note: The nutrient injection system on the back right. (From ZipGrow™, Cornwall, Ontario, Canada. With permission.)

FIGURE 14.34 ZipGrow™ microgreen system. (From ZipGrow™, Cornwall, Ontario, Canada. With permission.)

FIGURE 14.35 Plenty grow towers 16.4 ft (5 m) high channels. (From Spencer Lowell, San Francisco, CA. With permission.)

land, using 1% as much water. AeroFarms in New Jersey has nine indoor farms, which they claim get 130 times the amount of produce per acre.

Plenty grows plants on 16.4-ft vertical channels with LED vertical light banks between each row of plants (Figure 14.35). They, like all the other VFs, claim there is no need for pesticides as insects are prevented from entering the farm. Plenty uses cameras and sensors to monitor and control light, temperature, irrigation, and humidity levels. These systems would be very similar to greenhouse computer control technology. They use automated transplanters and harvesters to plant the towers from a central processing area (Figure 14.36). Transplanting is done in the central processing area (Figures 14.37 and 14.38). They grow leafy green mixes, herbs, kale, and lettuce.

Plenty indicates that labor is one of their larger costs and that automation with robotics is essential for economic success of all vertical farms. The greatest labor is in transplanting and harvesting. While robots can do some of the planting, harvesting, and logistics, experts oversee the crop development.

Several VFs exist in Canada. TruLeaf, in Nova Scotia, uses LED grow lights to produce leafy greens. There is one different approach to VF in Berlin, Germany called Infarm (www.infarm.com) that offers more than 20 in-store LED-powered grow modules for Berlin's retail supermarkets.

In 2005 Emirates Hydroponics Farm (www.emiratesfarms.com), located between Abu Dhabi and Dubai, started growing lettuce in a 1,000 m^2 greenhouse on vertically stacked shelves of NFT gutters with grow lights above each tier. They have now expanded to 10,000 m^2 of greenhouse lettuces and herbs. The greenhouse is 9 m tall with complete computerized control of the environment, CO_2 enrichment, and fertigation.

Badia Farms, Al Quoz, Dubai (www.badiafarms.com), grows microgreens, and mini leafy lettuces in an 8,500 ft^2 warehouse using vertical shelves with an ebb and flow tray system (Figures 14.39 and 14.40). Emirates Airlines in 2018 received $40 million for their Emirates Flight Catering facility located at the Dubai World Central near Al Maktoum Airport. They have partnered with Crop One Holdings (www.cropone.ag) of California to develop a VF of 130,000 ft^2 projected to produce 2,700 kg of leafy greens per day.

FIGURE 14.36 Central processing area. (From Spencer Lowell, San Francisco, CA. With permission.)

FIGURE 14.37 Transplanting station. (From Spencer Lowell, San Francisco, CA. With permission.)

FIGURE 14.38 Automated transplanting system. (From Spencer Lowell, San Francisco, CA. With permission.)

A company that focuses on manufacturing specialized VF equipment using aeroponic culture in tiered growing shelves is AEssenseGrows (www.AEssenseGrows.com). It is an American company with executive offices in Sunnyvale, California. Manufacturing is in Jiading, China. AEssenceGrows offers a line of aeroponic systems that are scalable from single-family operation up to large commercial vertical farming installations. The company's AEtrium System is optimized for continuous cultivation of cannabis, but is flexible to be capable of growing any plant that will fit within their shelves. Their "AEtrium Smartfarms" include SmartFarms that come in different model configurations for one-, two-, and four-layer growing environments. Cannabis seedlings, cuttings for clones, leafy greens, lettuce, and herbs each fit into the 4-layer SmartFarms with 24, 48, or 72 growing trays (Figure 14.41). Each unit is complete with a dosing injection system, LED lights and is mobile having castors (Figure 14.42). Irrigation pumps move water from the nutrient tank to the spray misters located under the growing trays (Figure 14.43). Aeroponic growth is fast because of optimum root oxygenation. A return pump moves water from the grow trays back to the reservoir. Sensors monitor and provide feedback to the computer system that manages water flow, pH, temperature, electrical conductivity (EC), CO_2 level, and light intensity. Each unit is shipped ready to assemble and put into production.

Dimensions of a 24-tray unit are 5.5 ft (1.68 m) wide by 10 ft (3 m) long by 8.33 ft (2.54 m) high occupying an area of 53 ft^2 (4.9 m^2). All models are of the same width and height. The length varies as they are modular. The first unit is the same as the 24-tray assembly, as it has the nutrient injection and controls attached. To expand, modules of 2 m in length are attached to the first unit. Thus, a 72-tray system is 23 ft (7 m) in length and occupies about 180 ft^2 (16.7 m^2) with aisle access space. The growing area is 100 ft^2 (9.3 m^2). It can produce about 5,000 lb (2,272 kg) of basil annually.

The company claims that the stacked 4-layer system produces 30–40 lb of leafy greens, herbs, or lettuce per square foot per year including the dosing footprint. The SmartFarm is an automated

FIGURE 14.39 Vertical farm with moveable shelves growing microgreens and leafy greens. (From Badia Farms, Dubai. With permission.)

FIGURE 14.40 Badia Farms seedling area. (From Badia Farms, Dubai. With permission.)

complete system; plug in water and power and it is operational. The leafy greens unit has adjustable shelves and lights for plant height from 9–12 in. (23–30 cm). The nutrient dosing controls are positioned at one end of the stacked towers for access for refilling (Figure 14.42). The grow trays are 23.9 in. (60.8 cm) x 29.5 in. (75 cm) x 7.9 in. (20 cm) deep. The nutrient reservoir is 80 US gal (364 L) with seven 4-L bottles for stock solutions. The irrigation timing is programmable, for example, 1 min "ON" followed by 3–15 min "OFF" with irrigation duration operated by the water sensors and computer manager program settings. Their "Guardian Grow Manager" software offers remote access and control of lighting, nutrient formulations, irrigation schedules, environmental monitoring and control, from any keyboard or smart phone.

FIGURE 14.41 AEtriumSmartfarm vertical farm on castors growing lettuce. (From AEssenseGrows, Sunnyvale, CA With permission.)

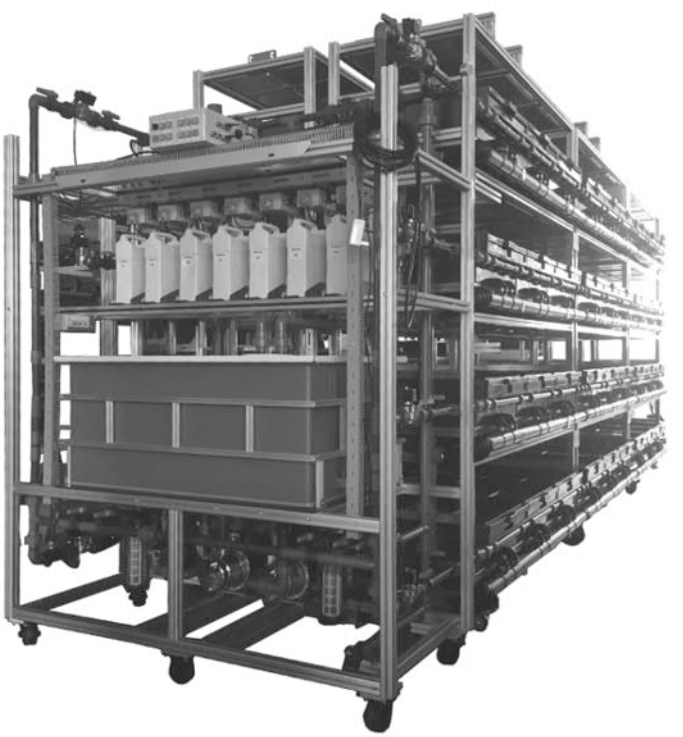

FIGURE 14.42 AEtriumSmartfarm vertical farm nutrient injection system. (From AEssenseGrows, Sunnyvale, CA With permission.)

FIGURE 14.43 Aeroponic growing tray with misters and plant roots. (From AEssenseGrows, Sunnyvale, CA With permission.)

FIGURE 14.44 AEtrium-4 aeroponic growing system for tall plants. (From AEssenseGrows, Sunnyvale, CA With permission.)

Seeds are sown in foam plugs in trays under mist and then transplanted to the AEtrium SmaratFarm grow trays. Each grow tray has 63 plant sites arranged 7 across by 9 lengthwise. A 24-tray unit has 1,512 plant sites. There is no automation in transplanting or harvesting.

As described above, seedlings or clones created from vegetative cuttings are transferred to the single layer or double layer AEtrium-4 tall plant environment, ideal for plants such as tomatoes, cucumbers, medical hemp, or cannabis (Figure 14.44).

The AEtrium-4 tall plant environment is a modular system that comes in 2 to 10 tub "trains" (10 tubs in a train are 4 ft x 50 ft) (Figure 14.45). There is one dynamic nutrient dosing matriarch at the head of the train. This matriarch samples, senses, doses nutrients, and irrigates the plants

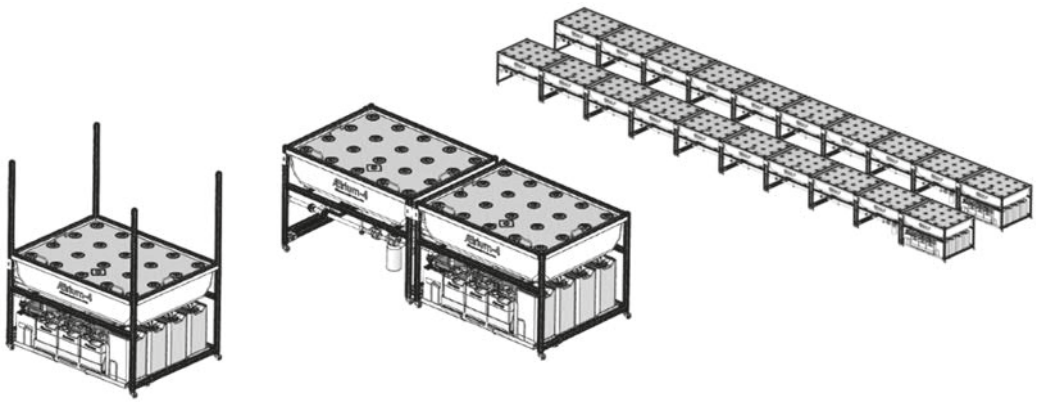

FIGURE 14.45 The AEtrium-4 is a modular system consisting of 2 – 10 tub "trains". (From AEssenseGrows, Sunnyvale, CA With permission.)

FIGURE 14.46 AEtrium-4 tubs with high density planting of cannabis. (From AEssenseGrows, Sunnyvale, CA With permission.)

on the specified irrigation cycle controlled by the sensors, pumps, and specified Guardian Grow Manager software controls. Nutrient formulations are composed from seven refillable individual liquid nutrient containers.

When optimized for cannabis, the AEtrium-4 can accommodate 1–20 large cannabis plants. Each tray is 16.7 ft^2 (1.6 m^2). The size is optimized for one standard grow light above each tray.

The compact, Ætrium-4 tubs assure that all plants get the same irrigation and nutrition, which may be hard to achieve in large grow trays. By utilizing the 20 grow sites with small, short plants; the Ætrium-4 can be configured for Sea-Of-Green (SOG/SCROG) high density cannabis cultivation for maximum yields (Figures 14.46 and 14.47)

FIGURE 14.47 AEtrium-4 cannabis growing system with moveable lighting. (From AEssenseGrows, Sunnyvale, CA With permission.)

Evergreen Farm OY (www.evergreenfarm.eu), located in Tampers, Finland is a fully automated VF using LED grow lights with their vertical cylindrical aeroponic growing system called "Grow 360" (Figure 14.48). This system is a structure composed of rotating cylinders in a growing platform 1.5 m. x 6 m. x 2.5 m. high (Figure 14.49). The Grow 360 is composed of 15 towers, each consisting of 12 panels holding 12 plants. One tower holds 144 plants so a growing unit has 15 x 144 = 2,160 plants in a foot print of 1.5 m by 6 m having an area of 9 m^2, which are 240 plants per square meter. With 18 harvests per year the annual yield of leafy greens with an average weight of 250 g per plant is 1,080 kg/m^2. This does not allow for aisle access, only the production of the unit space. Production can be increased by stacking the units up to four in height enabling production to be four times. Strawberries have also been grown successfully.

Each Grow 360 unit has 17 LED fixtures; one mounted vertically about 15 cm from each rotating tower of plants. The rotation of the towers can be adjusted from 0 to 15 times per minute. The lights can be placed close to the plants without any burn and the light is evenly distributed to each plant. Plants are fed from misters inside each tower with nutrients from a fertigation system. The recycled solution is monitored and adjusted by computer sensors and management. Proprietary software monitors with over 20 sensors and controls the surrounding environment, irrigation and nutrients, light, including cylinder rotation, RH, and temperature. Carbon dioxide is injected into the towers from above and air is blown up into the towers from below. Robotics is employed in harvesting and transporting using a robotic arm that can harvest strawberries and load them into a cart below that travels to the packing facility. The robotic arm has automatic exchangeable tools to harvest, transplant seedlings, and train the plants, such as removing dead leaves of strawberries.

In the United Kingdom, *Intelligent Growth Systems* has constructed an experimental VF near Dundee. It is to serve as an education center for anyone interested in the VF industry. The University of Nottingham has established the Centre for Urban Agriculture to train graduate students in Controlled Environment Agriculture (CEA) and especially vertical farming.

In Vienna, Austria, *The Vertical Farm Institute*, has a mission to specialize in the development of vertical farm operations in transparent (greenhouse type) structures to maximize utilization of sunlight rather than solely rely on artificial lighting in warehouses.

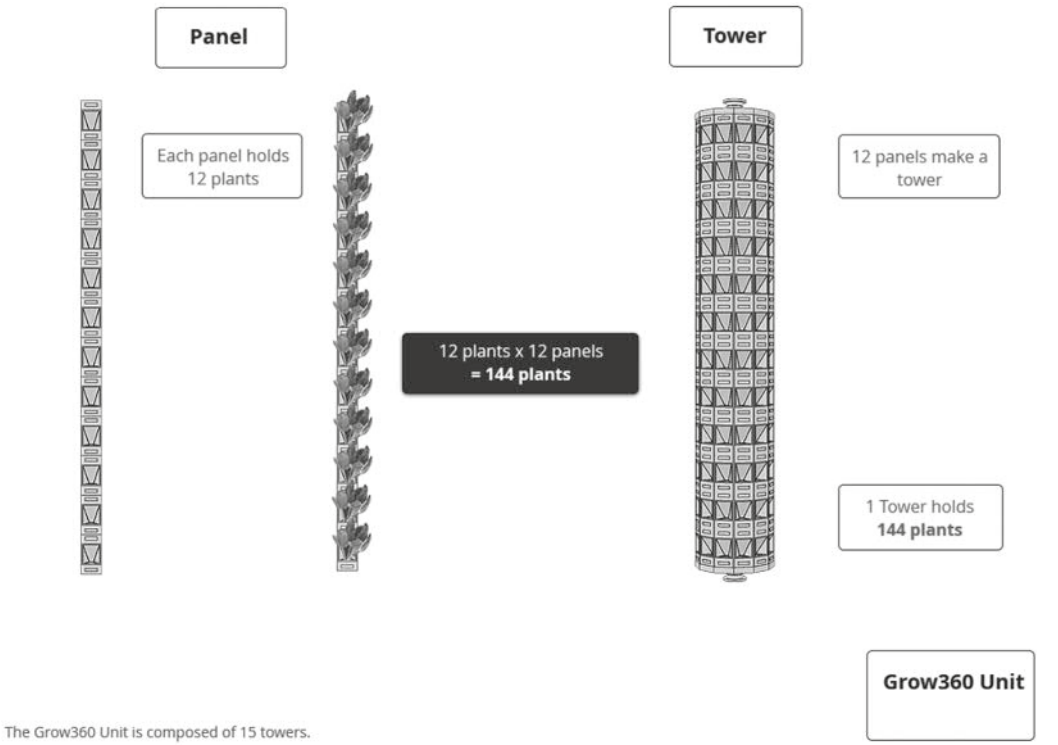
Panel
Each panel holds 12 plants
12 plants x 12 panels = 144 plants
Tower
12 panels make a tower
1 Tower holds 144 plants
Grow360 Unit
The Grow360 Unit is composed of 15 towers.

FIGURE 14.48 The Grow360 rotating plant tower of Evergreen Farm. (From Evergreen Farm OY, Tampers, Finland. With permission.)

FIGURE 14.49 The Grow360 unit consisting of rotating plant tower cylinders in a growing platform. (From Evergreen Farm OY, Tampers, Finland. With permission.)

14.6 CONTAINER VERTICAL GROWING

Freight Farms was the pioneer in developing the technology of growing plants vertically in containers. The use of 40-ft shipping containers for growing leafy greens and herbs began about 8 to 10 years ago (Figure 14.50). The concept was to use inexpensive containers that were no longer suitable for overseas shipping. The containers were modified to control temperature, humidity, and CO_2 enrichment. Artificial lighting was added using high-efficiency red and blue LED lights. The hydroponic system is a combination of ebb-and-flow troughs for the germination and seedling stage, followed by transplanting to vertical channels for growing the plants. The channels use a foam substrate similar to the ZipGrow towers. As the container is a complete operable unit that needs only a source of electricity and water, it can be set up anywhere, including in cities.

Freight Farms (www.freightfarms.com) with their "Greenery" growing system uses a vertical drip system of channels with foam to support the plants and distribute the nutrient solution within the channels. Seeds are sown in trays of peat plugs that are placed in an ebb-and-flow system for germination and seedling growth (Figure 14.51). The seedlings are transplanted into the foam substrate of the growing channels (Figure 14.52). Each growing unit is composed of five growing channels. The growing channels are supported by an overhead moveable mechanism that allows the growing towers and light panels to be positioned to get access by one aisle, thus maximizing the production area. LED arrays line the walls and hang between the growing trays (Figure 14.53). Each unit has 13,400 plant sites. The LED arrays and the plant panels hang vertically on a sliding rack system using a rack-and-pinion that allows moving them to facilitate harvesting and plant maintenance (Figures 14.54 through 14.56). Irrigation to the growing channels is from a drip system above each channel (Figures 14.56 and 14.57). Drip emitters are attached to an overhead main header pipe. Freight Farms recommends the growing of leafy greens, lettuces, herbs, and microgreens (Figure 14.58).

Freight Farms began in 2010. Their objective was to use decommissioned 40-ft shipping containers. Their first prototype was built in 2012 with initial sales in 2013 as *The Leafy Green Machine*. They claim in 2020 they have 300 farms operating in 48 U.S. states and 32 countries. Today they have new containers built to their specifications to meet high insulating standards to guard against outside temperature fluctuations, whether too hot or too cold. The containers are constructed of stainless steel and aluminum to avoid any moisture damage.

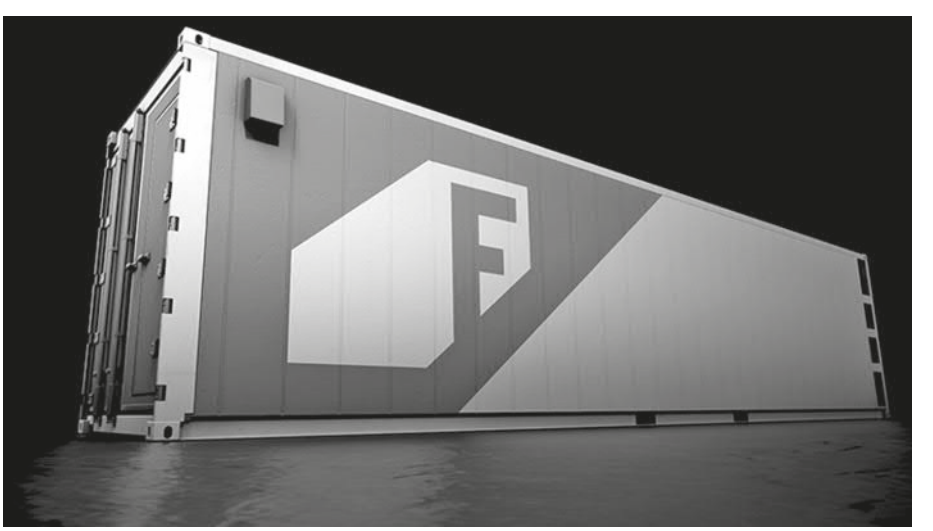

FIGURE 14.50 Shipping container vertical farm. (From Freight Farms, Boston, MA. With permission.)

FIGURE 14.51 Seedling ebb-and-flow chamber under the bench. (From Freight Farms, Boston, MA. With permission.)

FIGURE 14.52 Seedlings are transplanted from trays to the foam growing substrate within the growing channels. (From Freight Farms, Boston, MA. With permission.)

Grow Pod Solutions (www.growpodsolutions.com) has a basic "Eclipse Series Pod" that includes the insulated steel shipping container, cloud-based communication infrastructure, humidity control, electrical system, air conditioning-distribution system, hydroponic system, lighting, air purification, and CO_2 enrichment system. The growing system is a series of vertical trays similar to ZipGrow. They claim their units are scalable in size by stacking.

Some VFs started out using containers stacked vertically on one another in a warehouse. However, as the vertical farming technology developed it was discovered that growing as tiers within the warehouse with LED lighting between each was more efficient as the system could be automated much more than individual containers.

FIGURE 14.53 Three LED light banks, left, center, and right side with growing channels between. Note: The ventilation tubes between the LED light panels. (From Freight Farms, Boston, MA. With permission.)

FIGURE 14.54 Growing towers and light banks are moveable to allow easy access to crop. Note: The rack-and-pinion system on each panel to move the panels for access. (From Freight Farms, Boston, MA. With permission.)

FIGURE 14.55 LED lighting for normal growing cycle. (From Freight Farms, Boston, MA. With permission.)

FIGURE 14.56 Irrigation headers above with drip emitters and rack-and-pinion system in the middle for movement of the panels. (From Freight Farms, Boston, MA. With permission.)

Urban Crop Solutions (www.urbancropsolutions.com) based in Belgium, now with a North American office on the East Coast and representation in more than 20 countries, launched their *Modulex Plant Factory* in 2020. This plant factory is a scalable series of container growing units. Each container has an automated "*BenchCarousel*" (Figure 14.59) that moves the growing benches within each tier of the system allowing for the grower to monitor the crop and facilitate harvesting from one end of the container. Each grow module has its own climate and nutrient system so that different crops may be grown in different container modules. The company states that each growing bench can be brought to the operator within 90 seconds by the *BenchCarousel* (Figure 14.60). Each

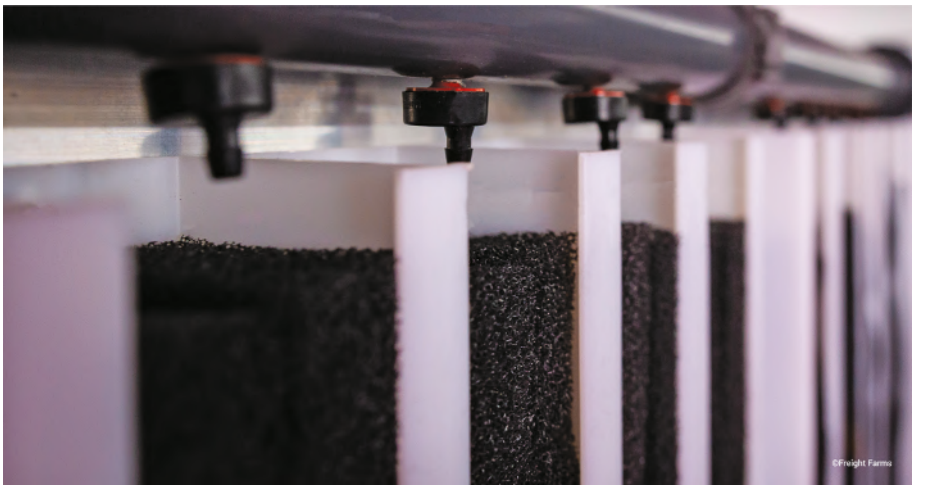

FIGURE 14.57 Drip emitters on irrigation header above apply nutrient solution to the foam substrate of each growing channel. (From Freight Farms, Boston, MA. With permission.)

FIGURE 14.58 Lettuce crop with LED light panel on right. (From Freight Farms, Boston, MA. With permission.)

40 ft insulated container accommodates 4 tiers of growing trays to give a total growing area of 86 m^2 (925 ft^2).

CubicFarm Systems Corp. of Langely, British Columbia, Canada, has developed automated, onsite indoor growing technology to grow fresh produce, herbs, and microgreens. A 40-ft module houses their patented cultivator technology with an undulating path that conveys interchangeable growing trays throughout the unit. These modules may be purchased individually, similar to the other vertical growing containers describe earlier, or they may be configured on a larger scale with 12 modules facing a central climate-controlled indoor onsite facility (Figure 14.61). The central climate-controlled workspace allows for easy cleanup during seeding, transplanting, harvesting, and packing.

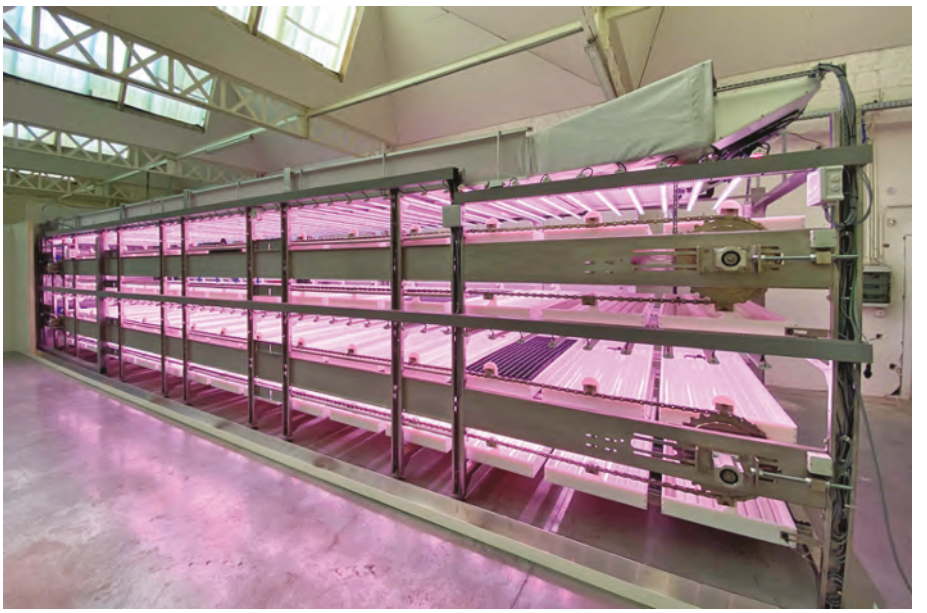

FIGURE 14.59 Container growing unit with conveyor system. (From Urban Crop Solutions, North America. With permission.)

FIGURE 14.60 Moveable growing trays of *BenchCarousel*. (From Urban Crop Solutions, North America. With permission.)

Each module can be configured with 250 trays of plants that follow the undulating path and rotate through the conveyor system every 90 to 120 min depending on the specifications for the crop (Figure 14.62). In an upward zigzagging path, the moving trays travel up toward the LED lights above and from the front to the back of the module. This moveable system has energy efficiencies and advantages over static or stationery systems in vertical grow towers with light banks

FIGURE 14.61 Central climate-controlled indoor workspace. (From CubicFarms, Langely, British Columbia. With permission.)

FIGURE 14.62 Open end of module with moveable conveyor showing easy access to crop. Note: The LED lighting and temperature control systems above and the irrigation system on right wall with nutrient tank below. (From CubicFarms, Langely, British Columbia. With permission.)

FIGURE 14.63 Fertigator module with batch tanks, stock tanks, and injection system. (From CubicFarms, Langely, British Columbia. With permission.)

between each tower of plants, as was described earlier for other container systems, because only a single row of lights located above the crop is needed. Plants grow in their normal horizontal position in NFT-type trays. Less space is required than other vertical growing because there is no need for aisles or scissor lifts for access since the plant trays cycle to the front of the module every 90 to 120 min. This path also enables the grower to inspect the crop to see that growth is optimum. The height of the container permits 7.5 trays stacked as they move on the conveyor system (Figure 14.62).

The trays move through an irrigation cycle where the nutrient solution enters the trays and exits at the opposite end to return to the nutrient tank. A complementary fertigator is located in a separate module. Nutrients are mixed and stored in 1,000 L batch tanks before being fed to the growing machine nutrient tank in each module. The distribution of the nutrient solution is monitored and can be controlled by CubicFarms' growing mobile app. The mixing of the nutrient solution is by use of a fully automated injector system (Figure 14.63).

Seeding, germination, and seedling growth takes place in a propagator module using the same undulating conveyor tray system. The enclosed propagator regulates its own lighting, CO_2 levels, nutrition, and water levels to provide optimum conditions for seedling development. The grow trays of seedlings ready for transplanting are removed as they travel to the front of the module. From there, the seedlings are transplanted into the trays of the cultivator manually. They are easily transplanted into the cultivator trays as they pass to the front of the module where they will continue along the path until harvest.

Each module has individual climate controls that may be adjusted for different crops and for different stages of plant growth and can all be done via CubicFarms' mobile app.

CubicFarms technology and growing systems are available globally with the ability to grow 365 days a year. They assist in design, training, automation, technology, marketing, and supply growing components such as nutrients, seeds, substrates, and so on.

14.7 ADVANTAGES AND DISADVANTAGES OF VERTICAL FARMING

The advantages of vertical farming are as follows:

1. Year-round crop production. Greenhouses also grow year-round.
2. It is Controlled Environment Agriculture (CEA) as are greenhouses.
3. Water usage is significantly less than field production due to less evapotranspiration and the recirculation of the water through the crop. Many VFs claim they use only 10% of the water for the same crops compared to that of conventional field production. Greenhouses with recirculation growing systems save equally as much water in crop production.
4. Less spoilage due to short transportation distances to local city markets.
5. Vertical farms utilize space efficiently with 1 acre of indoor space equivalent to 4–6 acres of field production.
6. Vertical farm growing systems can automate seeding, transplanting, and harvesting.
7. Abandoned warehouses within a city may be converted to VFs.

The disadvantages of vertical farming are as follows:

1. Not all crops can be grown in VFs. Their growing systems are only suitable to low-profile crops of high value such as leafy greens, arugula, bok choy, kale, leaf lettuces, herbs, and strawberries. Some medicinal crops can also be grown.
2. Energy input is enormous. Without natural sunlight, massive amounts of artificial light must be applied to satisfy the plants' photosynthetic requirements. Even for leafy greens and lettuces the daily light integral (DLI) needed is 17 moles/m^2/day with day length of at least 16 h.
3. The products of any VF must be superior in quality to that of field-grown product to obtain an "added value" price to be profitable because of higher production costs.
4. While VFs having a closed environment may deter pest and diseases, infestations may occur if rigid sanitation procedures are not practiced to prevent organisms from entering a building.
5. Automated VFs may maintain optimum growing conditions by use of computer sensors and controls, but, there is limited access to the crop by a qualified horticulturist. A grower does not have close examination of the crop to detect the presence of nutritional, environmental, and pest effects on a crop at an early stage when these issues can be rectified to prevent stress on the crop resulting in reduced yields.
6. Labor, followed by utilities, is the biggest cost of production causing many VF operations to be unprofitable. Vertical farming must use efficient growing systems that reduce labor cost and not require expensive automation to be economically viable.
7. Location of a VF must be in an area having adequate power and water to support all the environmental control systems as well as all growing and packing needs. It should also be located in an area, especially within a city, near good transportation routes as the product still must be shipped to a distribution center where deliveries are made to stores.

14.8 FINAL REMARKS

The greenhouse industry is highly technical and well established in controlling the greenhouse climate and crop growing needs using a weather station and crop sensors to monitor the systems constantly. Adjustments to optimize the crop environment are made by computer software and/or the grower. Greenhouses growing vegetables for nearby city markets could be located in urban "greenbelt" land near large cities within a 50-mile radius, such as exists near Vancouver, BC, Canada. Capital costs of greenhouses are much less than those of VFs. In addition, far less energy is needed as the natural sunlight can be utilized for the crop, which in fact, gives higher quality and yields than

the use of only artificial lighting from LEDs. In greenhouses, vine crops such as tomatoes, peppers, cucumbers, eggplants, and melons can be grown in addition to leafy greens, lettuces, and herbs that are presently only suitable to VF cropping systems.

However, there are many areas of the world where climates are not suitable to greenhouse growing of crops. These are regions of extreme low winter temperatures and those of high humidity. For example, growing in Sweden, Finland, Norway, Alaska, and other extremely cold regions where large cities are located, greenhouses lack light and lose a lot of heat during the winter season making costs of production high. In such areas artificial lighting would be needed during the short days of fall, winter, and early spring months. In such areas of extreme cold and low light it would be advantageous to grow in an insulated warehouse with LED lighting.

The most beneficial areas of the world for growing in VFs in an insulated warehouse would be in regions with high relative humidity. Asia, India, and the Middle East have many highly populated cities that have relatively large populations of middle-class residents who could afford high-quality, added-value products. While these regions have adequate sunlight and day lengths of 12–14 h year round, high relative humidity contributes to a very unfavorable environment for greenhouse growing. Cooling in greenhouses is by evaporative cooling, which is dependent on the RH of the ambient environment. The efficiency of evaporative cooling greatly decreases as RH increases until by 80% RH almost no cooling can be gained through evaporation of water. With high ambient light and temperatures the control of optimum greenhouse temperatures for most greenhouse crops cannot be achieved by evaporative methods, but, only with an air conditioning system (HVAC). Air conditioning in most cases is not economically viable for greenhouse crops. In this case, it would be advantageous to grow with VFs in insulated warehouses. Vast populations are situated in tropical and desert regions having high relative humidity and temperatures. VFs should focus on those areas as they also have large populations of middle class people who can afford to pay a higher price for quality produce.

Great potential for VFs exists in the development of efficient growing systems for fruiting, vine crops, such as tomatoes, peppers, cucumbers, melons, and eggplants. This is a greater market than leafy greens and the production of such vegetables would open new opportunities for supplying all fresh salad crops to the marketplace. Conventional field production of these vegetables is often of poor quality, shelf life, and questionable as to its safety from pesticides and human borne diseases, from lack of cleanliness. Pest and disease pressure under field production in these regions is extremely difficult to control without the use of hard pesticides. In vertical indoor farms many pests and diseases can be prevented from entering the growing environment and therefore greatly reduces the dependence on use of synthetic pesticides. That permits VFs to adopt an integrated pest management program (IPM) together with hydroponic systems to provide optimum plant nutrition to maximize crop yields free of pesticide residues. Good sanitation in VFs, through maintaining a sterile environment, yields crops free of bacteria and other organisms causing human illness, which results in high standards of food safety. All of these factors give indoor VF production a market advantage that is presented in distinctive packaging to differentiate products of added value.

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15 Tropical Hydroponics and Special Applications

15.1 INTRODUCTION

Over the past 25 years, there has been a great interest in hydroponics in tropical countries worldwide (Lim, 1985; Resh, 1998; Resh et al., 1998; Rodriguez Delfin, 1999a, 1999b; Mills, 1999; Furukawa, 2000; Wilson, 2000). A lot of commercial hydroponic operations have begun in Australia, China, Indonesia, Mexico, Central and South America. In February 2011, news (www.freshplaza.com) was released on the opening of the largest greenhouse in Australia. It is located near Adelaide at Two Wells. The $65 million, 17-ha (42.5-acre) facility was projected to produce 11 million kilograms of truss tomatoes annually. The company is d'VineRipe (http://dvineripe.com.au). They are using the raised trays with rockwool substrate slabs. By 2021 they have gone through four expansions with a total area now of 43 ha (106 acres). Flavorite Group has 26 ha (64 acres) of greenhouses with an additional 4.5 ha (11 acres) under construction in Warragul, Victoria, Australia. They grow tomatoes and peppers.

As economies in some of the less developed countries improve with control of inflation and political stability, the standard of living will rise. With improved economic conditions, new opportunities create a larger middle class of people who can afford to demand higher quality fresh vegetables. Brazil is an example of this progress, and a substantial hydroponic greenhouse industry is developing. At present they are focused on arugula, lettuce, and herbs.

Awareness of quality vegetables opens a market for controlled-environment agricultural crops such as tomatoes, sweet peppers, lettuce, watercress, and other herbs. These will be grown hydroponically to ensure that they are free of organisms that may cause diseases such as dysentery and cholera. In tropical areas, most agriculture is located in valley bottoms where water is more plentiful; however, such areas, especially close to large cities, are often polluted due to runoff from residences. This was the reason for the success of Hidroponias Venezolanas in Caracas, Venezuela, in hydroponics (http://hidroponiasvenezolanas.com). This operation is used as an example of the potential use of hydroponics in tropical regions.

15.2 HIDROPONIAS VENEZOLANAS

In the region where Hidroponias Venezolanas facility was established, local field growers of lettuce and watercress located in valley bottoms used runoff from the surrounding terrain that swept disease organisms into their crops. Much of this product went to restaurants where clients often became sick with dysentery after consuming the fresh salads. This provided an opportunity for Hidroponias Venezolanas to grow salad crops hydroponically with clean, mountain spring water available only on the steep inclinations of the mountain slopes, well above any agricultural field operations. In this situation, the hydroponic farm site was well above any farms or residences, and the area above was a park. Nonetheless, chlorination and filtration systems were installed to guard against any bacterial infestation.

Growing temperate crops in tropical countries presents some unique challenges. With improved economies in many of the tropical countries, an expanding middle class of people demand clean, safe, and nutritious foods, as they do in other industrialized countries throughout the world. They demand similar diets that include fresh fruits and vegetables.

DOI: 10.1201/9781003133254-15

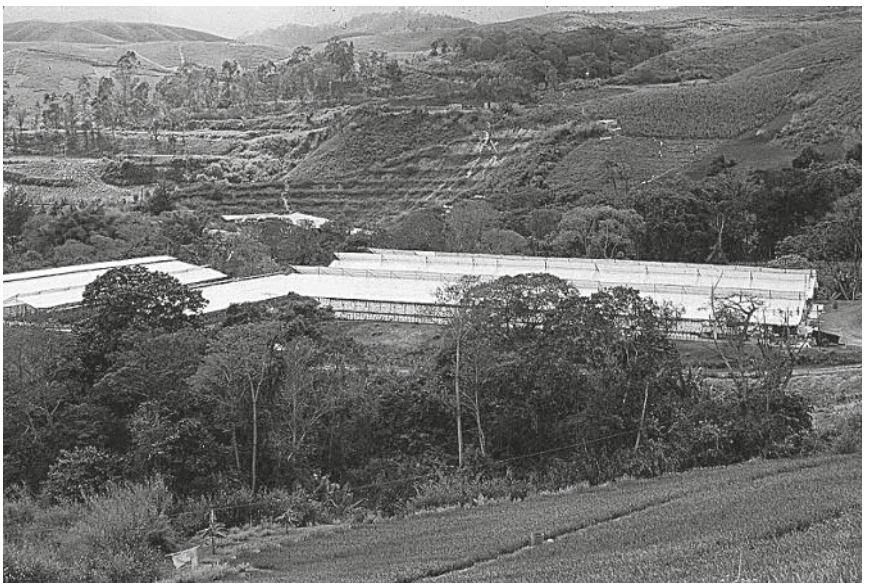

FIGURE 15.1 Steep terrain of conventional farming with terraces of hydroponic culture under plastic covers. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

Such crops, which are not native to the tropics, require specific growing conditions and culture. Strawberries, sweet peppers, eggplants, tomatoes, cucumbers, lettuce, cabbage, celery, cauliflower, beans, watercress, and other herbs are in demand. In many regions of these countries, the climate is not suitable for growing such crops because of excessive temperatures and high humidity. However, in mountainous areas with elevations above 1,500 m (4,900 ft), the temperatures drop sufficiently to allow the growing of cool-season, temperate crops, such as lettuce, strawberries, watercress, cabbage, celery, and cauliflower. Such is the case in Venezuela.

The temperatures in these regions range from 22–28°C (72–82°F) during the day and from 16–20°C (61–68°F) during the night. Daytime temperatures are at the upper limit of the tolerable range for growing cool-season crops such as lettuce, cabbage, cauliflower, and watercress. Any prolonged variation in daytime temperatures can cause crop failure.

The higher the elevation the crops can be located at the less the chance of experiencing excessive daytime temperatures, which may cause bolting of lettuce, cabbage, and cauliflower or the flowering of watercress. By seeking higher elevations, generally steeper terrain is encountered (Figure 15.1). As a result, conventional farming is very difficult. Small plots of land are cultivated by hand repeatedly year after year. Production declines with fertility, and soil erosion increases with structural breakdown.

15.3 SAND CULTURE IN THE TROPICS

The farm of Hidroponias Venezolanas is located about 40 km from Caracas, in San Pedro de Los Altos. Terraces have been cut into the steep terrain to maximize the available level ground (Figure 15.2). Each terrace is about one-third of a hectare. As the soil is very rocky and the use of heavy equipment to level the sites is costly, it was decided to construct raised beds of metal frames. The cost of steel and the labor of welding it are relatively low.

The frames of the beds were welded on-site and set into concrete footings as shown in Figure 15.3. The bottoms were constructed of clay bricks and concrete, common building materials of the

FIGURE 15.2 View of hydroponic terraces at the farm of Hidroponias Venezolanas. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

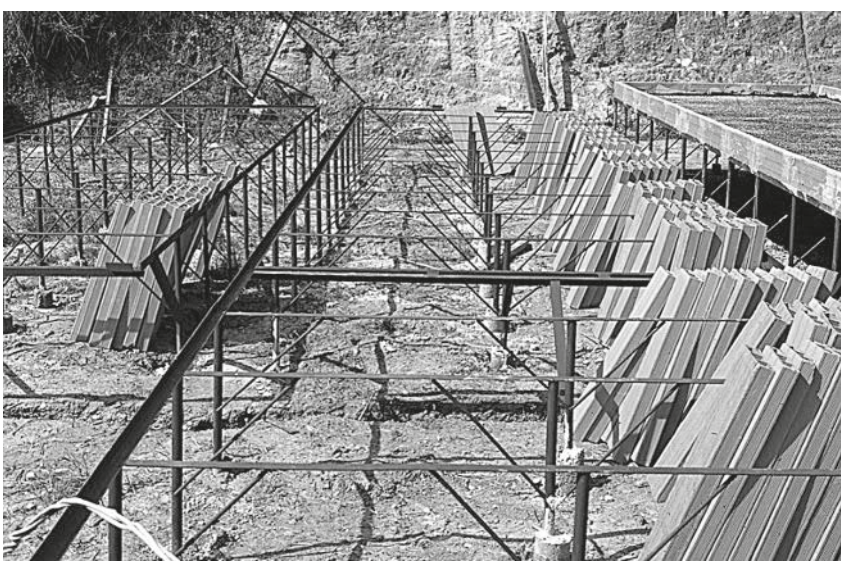

FIGURE 15.3 Steel frames of hydroponic beds. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

country (Figure 15.4). The beds were leveled with a thin coat of concrete and sealed with bituminous paint (Figures 15.5 and 15.6). Drain pipes or clay tiles are placed on the bottom surface to provide adequate drainage (Figure 15.7).

The substrate is quartz (silica) sand with a subirrigation system. Large 50,000-L (13,000-gal) underground cisterns of concrete were built for storage of nutrient solution. Fresh water is pumped from several wells and streams to a number of storage tanks and finally to one above the hydroponic

FIGURE 15.4 Clay brick bottom of hydroponic beds. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

farm. The water is low in total dissolved salts, a rare and fortunate situation in the tropics. A complex series of piping and plumbing moves the water to the storage tanks. A nutrient solution cistern with a series of beds forms one sector of production. The solution is distributed via pipes and pumps to distribution pipes in each bed.

The beds are flooded at one end by entering a PVC header attached to fill-drain lines along the bed length (Figures 15.7 and 15.8). Clay tiles cut in half or PVC pipes with holes placed along the bottom of each bed distribute flow evenly. The drain is plugged manually to allow the solution to rise in the bed to within an inch (2.5 cm) of the sand surface (Figure 15.9). Three pipe plugs of different heights regulate the solution level in the beds. When transplants are first placed into the beds, the tallest pipe plug maintains the level within 1 in. Later, as plants become established, the water level is decreased several times by placing shorter pipe plugs in the drain hole.

Each irrigation cycle takes from 15 to 20 min. The plug is then removed, and the solution flows out of the bed within 10 min, providing good aeration. Four to five irrigation cycles per day are needed for the lettuce. To reduce the drain-fill times, new beds are shortened to 9 m (29.5 ft), instead of the previous 18–20 m (60–65 ft). The large cistern is divided into five sections of 9,000 L (2,375 gal), with each section having a separate pump and piping to a sector of eight beds (Figures 15.9 and 15.10). This permits filling of the beds within 5 min, with a similar drainage time, resulting in improved oxygenation of the plant roots.

FIGURE 15.5 Beds leveled with a coat of concrete. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 15.6 Beds sealed with bituminous paint. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 15.7 Drain-fill lines in bottom of beds. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 15.8 Nutrient solution enters from main distribution lines to inlet line end of the beds. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

Suitable silica sand must be trucked from a distance of over 500 mi and is hence costly. The sand is pure silica of coarse texture normally used in the glass industry. Owing to this high cost of silica sand, placing a 3- to 4-in. (7.5–10-cm) layer of crushed clay bricks on the bottom of the beds over the drain lines reduced the sand requirements. Silica sand was placed on the remaining 4–5 in. (10–12.5 cm) of the depth on top of the crushed bricks. The use of crushed clay tiles as a lower medium

FIGURE 15.9 Inlet mains and drainage ends of beds. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 15.10 Distribution system from multisectioned cistern that provides solution to sectors of beds. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

created problems because of its breakdown into a fine powder over a period of 6 mo. This powder plugged the drainpipes, causing excessive moisture in the roots and crown of the lettuce plants contributing to bacterial soft-rot. The solution was to remove the lower layer of crushed clay tile and replace it with coarse granite rock followed by a layer of smaller pebbles before the top layer of sand was added (Figure 15.11).

FIGURE 15.11 Coarse rock with pea gravel and finally a top layer of coarse sand. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

The availability and cost of construction materials, medium, and fertilizers in a specific location will determine the type of hydroponic system that should be used. In many tropical countries, lumber is scarce and very costly. Generally, steel products, concrete, and clay bricks are readily available and inexpensive. Such is the case in Venezuela, where hydroponic beds are constructed of steel frames, clay bricks, and concrete as outlined above.

In the tropics, where daylength and the hours of sunlight vary only slightly from one month to the next, an accurate correlation should exist among electrical conductivity (EC), total dissolved solutes (TDS), concentration of various nutrients, and plant age. There are two seasons in the tropics, a wet season from June through December and a dry season from January through May. While there is more precipitation during the wet season, rainfall is very heavy and over a short period of time each day. Rapid clearing of the sky follows with full sunlight. Therefore, the number of hours of sunlight for any month during the wet season does not differ greatly from that of the dry season. Consequently, the most significant effect upon nutrient solutions is that of plant growth stage, rather than the influence of sunlight.

Extremes in rainfall are commonplace. For instance, in the plains of central Venezuela, during the dry season, precipitation is so low that it closely resembles desert conditions with extremely high temperatures over 30°C (86°F), while during the wet season, rainfall is so heavy that the entire region becomes inundated with several feet of water. In such areas, crops can only be grown during the dry season with irrigation.

Even in the mountainous regions the wet and dry seasons are distinct. During the wet season, temperatures are generally a few degrees warmer, and rainfall occurs for several hours almost every day. As a result, crops that cannot tolerate continual moistening are soon damaged and infected with diseases. Such is the case with lettuce, especially head lettuce. Within several weeks of maturity, head lettuce is very sensitive to moisture. Any moisture that penetrates the head causes rotting, which spreads rapidly with high temperatures. Losses of up to 40–60% are not uncommon.

Since many crops cannot be cultivated during the wet season, short supply raises prices dramatically. An excellent market can be established for hydroponically grown lettuce and other produce if

the market can be reliably supplied year-round. Using sand culture in raised beds prevents rainfall from upsetting the growing of crops through excessive root moisture, but moisture onto the plants still causes losses. Several methods help overcome this problem. First, the choice of a very resistant variety that has tightly closed leaves will prevent rainfall from entering the head. Hidroponias Venezolanas has tested over 25 different varieties and found that the best are "Great Lakes 659" and "Montemar." These are resistant to bolting and form large heads. The second possibility was to erect an inexpensive roof above the beds. Placed at several meters above the beds in a saw tooth configuration, the roofs would prevent rainfall, but permit sufficient natural ventilation to keep temperatures within several degrees of ambient. Fiberglass covers were constructed. The material discolored within a year and light levels reduce sufficiently to cause bolting at the slightly higher than ambient temperatures.

My experience with the hydroponic farm at CuisinArt Golf Resort & Spa in Anguilla indicates that a polycarbonate material, such as GE's "Lexan," does stand up to the high ultraviolet light of the tropics. After 16 yr, the greenhouse in Anguilla showed very little degradation in light transmissibility of the polycarbonate. The best material for permanent structures in tropical regions would possibly be the twin-wall or triple-wall polycarbonate products, as they would also give higher insulating values than the corrugated, single layer product. There are other cheaper Chinese products of polycarbonate available, but how they compare with the GE Lexan cannot be predicted. Many of the greenhouse polycarbonate materials, such as "Lexan," have a 10-yr guarantee against yellowing and loss of light transmission.

Growing of head lettuce in areas of high temperatures, 25–28°C (77–82°F), is difficult because of "bolting," which occurs above these temperatures. With a slight reduction in light from the use of a fiberglass or polyethylene cover, bolting occurs at lower temperatures (25–27°C).

For this reason, a temporary cover that could be easily and quickly removed would be beneficial to the growing of many cool-season crops. Polyethylene retractable roof greenhouse now available commercially by manufacturers such as Cravo Equipment Ltd., Brantford, Ontario, Canada (www.cravo.com), may be the answer for the tropics (Chapter 12, Section 12.10). Motorized roll-up roofs may be deployed within several minutes. The roofs cover the crop as soon as rain is detected and open when the threat of rainfall passes. In this way, the crop still can grow under ambient temperatures and light, reducing the incidence of bolting and bacterial soft rot.

In the tropics, year-round warm temperatures generate large insect populations. When crops are grown hydroponically outside without the protection of closed greenhouses, insects quickly invade the crops and rapidly spread with few or no natural predators. The use of pesticides is imperative. Often pesticides are unavailable and those, which are, may soon become ineffective due to the buildup of insect resistance. Without the introduction of new pesticides to overcome such resistance, control diminishes until crop losses occur.

Leaf miners infesting the lettuce are difficult to control. Assisting control is a natural predatory wasp. In the future, predators must be imported or local laboratories established to raise them in order that a good integrated pest management (IPM) program can be the principal method of control. These control measures of pests are discussed in Chapter 16.

Nematodes infest most soils in tropical countries. These are very small, microscopic roundworms, sometimes called *eelworms*, which infest the roots of plants. Depending on the species involved, they may cause death of roots, injuries to roots that act as ports of entry for fungal diseases, or swelling of roots so that they cannot function in normal water and mineral uptake. This root damage often causes plants to wilt during the day when water uptake cannot meet evapotranspirational losses. If plants do survive the stress, they become stunted and non-marketable.

Soil temperature is critical in the development of nematodes. Females fail to reach maturity at temperature above 33°C (92°F) or below 15°C (59°F). Soil temperatures in the tropics are near optimum levels for nematode development. It takes about 17 d at 29°C (85°F) for females to develop

from infective larvae to egg-laying adults. Spreading within the field occurs through movement of infested soil or plant debris by man, water, and wind.

Even with hydroponic culture, nematodes can easily be introduced into a crop by movement through water or wind. Preplanting treatments with steam or chemicals effectively eliminate nematodes from soil and other media such as sand, sawdust, or gravel used in hydroponics. Nematodes are killed with steam sterilization, by heating the medium under moist conditions for 30 min to 49°C. (120°F) (Refer to Chapter 4 on steam sterilization.)

To control nematodes in the past Hidroponias Venezolanas used steam sterilization generated by a portable steam boiler. Perforated pipes were placed several inches below the surface of the medium in the beds. The entire bed was covered with a heavy vinyl or canvas tarpaulin. Hidroponias Venezolanas no longer uses steam sterilization to control nematodes. Between lettuce crops they flood the beds with water for several hours to float the old roots to the surface, removing them by hand. After draining, the beds sit empty for several days. Sunlight raises the temperature of the sand sufficiently to kill any nematodes. The beds could be covered with black polyethylene to assist in raising the temperature of the sand below. In addition, with chlorination and filtration of all the raw water entering the hydroponic systems, these organisms are substantially reduced.

Once this multitude of problems can be resolved, excellent lettuce crops can be grown under tropical conditions using hydroponics (Figure 15.12). When most problems were resolved, each hydroponic bed 2.5 m x 20 m x 25 cm deep (8.4 ft x 65.6 ft x 9.8 in. deep) was capable of producing 310–330 heads of lettuce, each averaging 1 kg (2.2 lb) in weight. In a continuous cropping system, new plants were sown every day so that harvesting could be done at least three times a week. In this way, the market can be supplied year-round.

Consistent supply to the marketplace is essential if long-term contracts are to be met. This reliable servicing of the market is the basis for establishing a strong market, with a constant premium price to be received for the hydroponic products.

Head (iceberg) lettuce takes between 70 and 75 d from seeding to harvest. The lettuce seedlings are started in a special propagation area. Seeds are sown into petroleum-based synthetic "Lelli"

FIGURE 15.12 High-quality head lettuce produced from sand culture. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

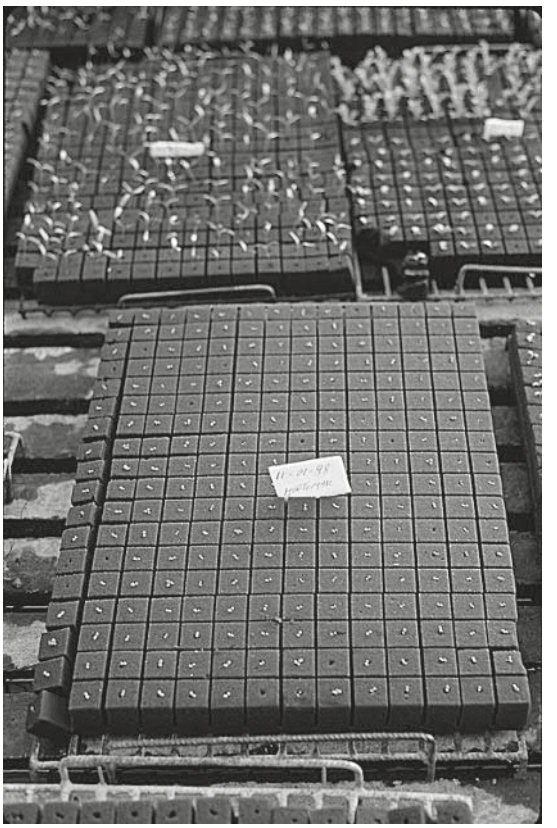

FIGURE 15.13 Propagation of lettuce seedlings grown in "Lelli" cubes. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

cubes, similar to "Oasis" cubes measuring about 1-in. x 1-in. x 1.5 in. high (Figure 15.13). After seeding, the cubes are placed under a screen for 4–5 d until they germinate (Figure 15.14). This prevents birds from eating the seeds. They are separated and spaced out in special channels of an ebb-and-flood bed to continue growing until they are 25–28 d old (Figures 15.15 and 15.16). At 25–28 d they are transplanted directly into the sand culture beds. The lettuce reaches maturity within 42–45 d after transplanting. Yearly production of one hydroponic bed would be eight to nine crops of an average 320 heads or 2,500–2,800 heads of lettuce.

15.4 EBB-AND-FLOOD WATER CULTURE OF WATERCRESS

The disadvantages of unavailability and high costs of materials and equipment can be overcome by use of water cultural and nutrient film technique (NFT) systems of hydroponics. While little commercial application of NFT has been carried out in the tropics, it does offer a vast potential by reducing capital costs and dependency on suitable media such as granitic sand or gravel, which is often rare and expensive. Watercress is grown at Hidroponias Venezolanas in raised beds with a modified NFT or ebb-and-flood system. Raised beds of metal frames and clay bricks are constructed as described earlier for sand culture (Figures 15.3 through 15.6). The difference in the bed structure is only the narrower width and shorter length, about 1 m x 8 m (3.3 ft x 26 ft).

Large 50,000-L (13,200-gal) cisterns store the nutrient solution to each sector of beds. No medium is used with the watercress. The solution is maintained at 1–2 cm depth and is circulated every 15

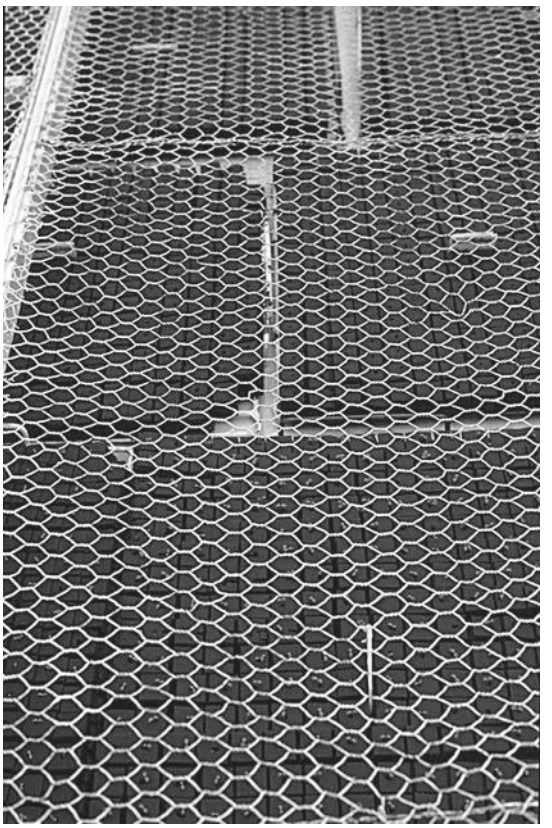

FIGURE 15.14 Initial germination of lettuce under screen cover. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 15.15 After 15 d the seedlings are separated and placed in ebb-and-flood channels. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 15.16 At 27–28 d the seedlings are ready to transplant. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 15.17 PVC piping distribution system. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

min for 5 min during daylight hours. The solution is pumped through 3-in. (7.5-cm)-diameter main PVC pipes located above the beds (Figure 15.17). Inlet tubes of 0.5-in.-diameter black polyethylene hose direct the solution from the mains to each bed at one end (Figure 15.18).

The solution flows to the other end, draining to an 8-in. (20-cm)-diameter catchment pipe that returns the solution to the cistern. This is an ebb-and-flood system.

FIGURE 15.18 Inlet black polyethylene tubes from 3-in. main. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

Not all of the fertilizers normally used in a watercress formulation in North America are available in Venezuela, so substitutions need to be made. Diammonium phosphate is used in place of monopotassium phosphate as a source of phosphorous. Similarly, iron sulfate is substituted for ion chelate. Both of these compounds are less soluble than their counterparts used in North America.

The climate at the farm, whose elevation is 1,300 m (4,265 ft), has moderate temperatures from daily maximums of 26–28°C (79–82°F) to nightly minimums of 15–18°C (59–65°F), which are fairly ideal for watercress. Since flowering does not occur, there is no need to start the plants from seed. Cuttings are taken from existing plants to transplant into new beds. The cuttings are placed into the beds containing about 1–1.5 cm (0.5 in.) depth of solution (Figure 15.19). Within 4 wk the watercress is ready to harvest.

The plants are changed every 6–8 mo, as root buildup in the beds reduces flow of the solution and consequently oxygen to the roots (Figure 15.20). This leads to root decay and diseases, which reduce productivity.

In addition, the plants should be rejuvenated at least once a year through sowing of seeds to maintain vigor. Seed is sown directly into several beds having a mixture of coarse sand and pea gravel. The beds are subirrigated to within 1 cm of the surface to keep the seed moist. Within 5–6 wk the seedlings are removed with their roots intact and transplanted to the production beds. They are about 4–5 cm (2 in.) tall at that age.

The product that is sold to restaurants is shipped bulk as 0.5-kg (about 1-lb) bundles in returnable plastic tote bins (Figure 15.21). Several centimeters of water is kept in the bottom of the bins to retain freshness of the watercress. For supermarkets, the watercress is packaged in 100-g (3.5-oz) plastic bags (Figure 15.22). The bulk product is harvested at from 25–28 d to provide it with longer stems, which the restaurants use in soups and a dip paste, whereas the packaged watercress that goes to the consumer is harvested from 14 to 16 d to obtain more succulence for fresh salads.

Monthly production of 6,000–8,000 kg (13,000–17,600 lb) comes from an area of about 0.5 ha (1.25 acres) of beds. This is equivalent to 1.2–1.6 kg/m^2 (0.25–0.33 lb/ft^2). The objective of using improved bed design, higher quality fertilizers, and new methods of nutrient solution circulation is to obtain 2 kg/m^2 (0.4 lb/ft^2) of watercress.

FIGURE 15.19 Watercress cuttings placed in beds to start a new crop. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

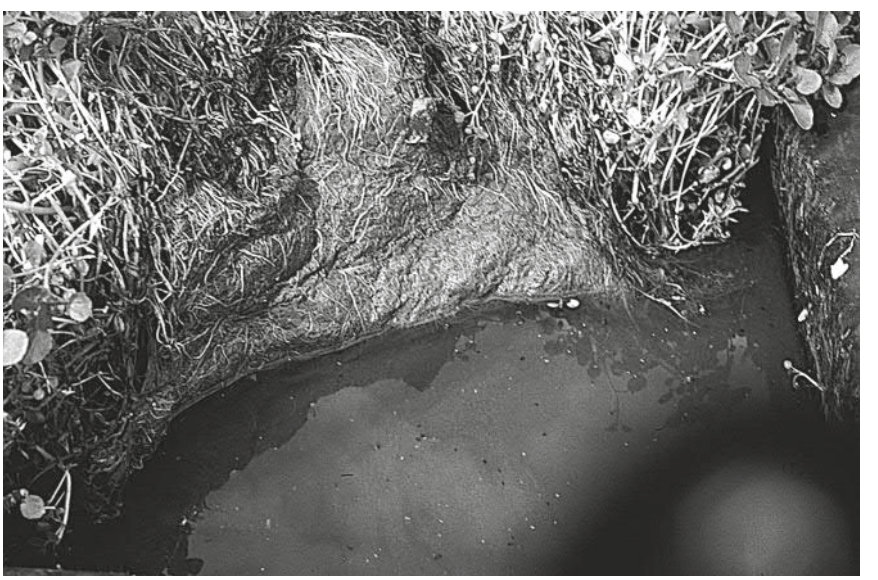

FIGURE 15.20 Large root mass after 6 – 8 mo of growth impedes flow of solution. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

Continued increasing demand for high-quality, clean watercress in the marketplace is forcing the company to expand to more growing terraces. As their volume increases, they have upgraded their packing facilities with more technical weighting and packaging equipment.

FIGURE 15.21 Packing of watercress in returnable plastic tote bins for restaurants. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 15.22 Packaged watercress for supermarket sales. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

15.5 RICE HULLS-COCO COIR CULTURE OF TOMATOES, PEPPERS, AND CUCUMBERS

Three terraces of "greenhouses" of total area of 5,800 m^2 (62,400 ft^2) were constructed in 1996. These are light steel frames with a polyethylene covering to protect the crop from rainfall (Figure 15.23). Tomatoes are the principal crop, with some production of bell peppers and European cucumbers. Similar to lettuce, the plants are seeded in "Lelli" cubes in a propagation area (Figure 15.24) with ebb-and-flood irrigation.

Initially, the plants were grown in 5-gal black polyethylene nursery bags with 85% rice hulls and 15% fine sand. From two 35,000-L (9,250-gal) tanks located above the terraces, the plants were fed by gravity with a drip irrigation system. During the first crop it was discovered that the substrate did not retain sufficient moisture, resulting in blossom-end rot (BER) of many fruits. Even two drip lines per bag did not prevent BER. To overcome this problem, the company located a source of coconut coir that could be shipped bulk. The substrate was changed to 70% coco coir and 30% rice hulls (Figure 15.25). The cost of both coco coir and rice hulls was very low. Coco coir then cost about $15 per cubic meter and rice hulls cost about $10.50 per cubic meter delivered to the farm.

As the plastic nursery bags break down under the intense tropical sunlight, they were replaced with 5-gal plastic paint buckets (Figures 15.23, 15.26, and 15.27). Small holes were drilled around the base of the buckets for drainage before filling them with the coco coir-rice hull mixture. The cost of the substrate per bucket was about $0.30. They began by growing only one plant per bucket, but later used two plants per bucket as is done with perlite bato-buckets as described in Chapter 13.

The plants can be trained in a V-cordon method. The problem of BER was overcome, but there was still a lot of stem disease, especially in the crown area. This disease causes wilting and death of many plants when they begin producing heavily. The problem was related to contamination of the coco coir. The coco coir must be steam sterilized to pasteurize the coco coir and rice hulls before placing the substrate in the buckets. Alternatively, the substrate could be moistened on a concrete slab

FIGURE 15.23 Inexpensive polyethylene covered structures. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

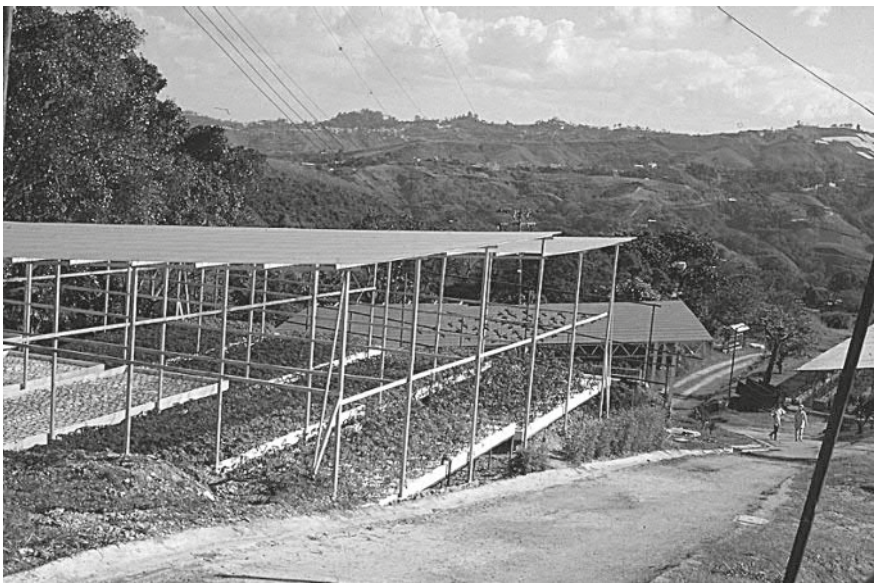

FIGURE 15.24 Tomato seedlings in propagation area. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 15.25 Tomatoes growing in 5-gal plastic bags of coco coir and rice hulls. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

FIGURE 15.26 Five-gallon plastic buckets for growing tomatoes. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

that was clean and covered with black polyethylene. Sunlight on the black polyethylene cover would quickly raise the temperature of the substrate sufficiently to pasteurize it. The principal tomato variety used was Agora, a Vilmorin seed. It yielded very heavily in the first five to six trusses, but soon succumbed to the wilt disease.

Trials with peppers and cucumbers were carried out to determine the best varieties for the tropical climate. Such trials must be ongoing to test new cultivars as they are introduced. Varieties for tropical regions must have resistance to common fungal diseases such as powdery mildew. We found in Anguilla that "Dominica," a DeRuiter variety, is one of the best European cucumber varieties for resistance against powdery mildew. With continued improvement in sterilization of the substrate and pest control, successful crops may be grown in tropical regions (Figure 15.27).

High population centers with rising economies increase the percentage of middle-class people who are able to be selective in their food demands. This creates a strong market for high-quality products normally not achieved by conventional soil culture. Hydroponic crops of clean, superior quality find the marketplace willing to pay a premium price. This higher return for products grown hydroponically justifies the high initial capital costs of establishing a hydroponic farm in tropical countries. It will support the imported technology required for successful operation of hydroponics and training of local workers.

15.6 PERU HYDROPONICS

15.6.1 Universidad Nacional Agraria La Molina

In 1994, Dr. Alfredo Rodriguez Delfin and Milagros Chang La Rosa established the Centro de Investigacion de Hidroponia y Nutricion Mineral (CIHNM) at the Universidad Nacional Agraria La Molina (UNALM), in Lima, Peru. They developed a hydroponic nutrient formulation, *Solucion Hidroponica La Molina*, for people interested in growing hydroponically. At the same time they began offering courses, *Hydroponics Workshop Course*, at a national level. By 2017 CIHNM had presented 226 practical courses with 7,000 participants and 17 international courses of hydroponics with participants from South America, Central America, Mexico, North America, and Europe. The

FIGURE 15.27 Successful tomato crop growing in coco coir and rice hulls. (From Hidroponias Venezolanas, S.A., Caracas, Venezuela. With permission.)

21st Hydroponics International Course was held in August 2019 (Figure 15.28). The CIHNM offers distant learning courses by Internet and social media. They present live video courses by various hydroponic experts from different countries.

The CIHNM has a 750 m^2 and a 500 m^2 demonstration/experimental area of various hydroponic systems growing many different crops. This area is to show students of the different faculties of the UNALM and the public that visit the university, the potential of hydroponic culture. The hydroponic systems include: NFT, drip irrigation, column culture, and soilless substrate methods. Crops grown include lettuce, herbs, leafy greens, eggplants, peppers, tomatoes, cucumbers, strawberries, beans, cabbage, celery, chard, kale, peas, watercress, and radish (Figures 15.29 and 15.30). The center has derived a number of nutrient formulations for sale to the public interested in starting a hydroponic growing system.

The CIHNM offers a newsletter, *Red Hidroponia*, which has technical articles presented by various hydroponic specialists from Latin America and other regions. The activities of CIHNM include research, teaching, and extension to individuals and commercial growers. These activities have led to assisting in the establishment of commercial hydroponic operations in Peru and other South American countries.

15.6.2 Invernaderos Hidroponicos del Peru

Invernaderos Hidroponicos del Peru, SAC, is the largest hydroponic greenhouse in Peru. It is located in Lurin District, 32 km south of Lima, Peru. It has been in production for 20 years and markets the products under the name *Don Miguel*. There are five houses of screen or polyethylene, each of 5,000 m^2 (53,800 ft^2). The total area is therefore 25,000 m^2 (269,000 ft^2). Two of the screen houses are for lettuce production in NFT. The NFT system is constructed of 3-in. PVC pipes (Figures 15.31 and 15.32). Some experimentation is being done with A-frames of NFT pipes (Figure 15.33). There are 24 beds per house, each bed producing 6,000 heads of lettuce per month. That is, a total of 24 x 6,000 = 144,000 heads per month per house. For the two houses of lettuce monthly production is 288,000 heads.

FIGURE 15.28 21st International Course-Milagros Chang La Rosa-front row far left, Alfredo Rodriguez-Defin, front row next to author under "Hidroponia" of sign. (From Centro Investigacion Hidroponia y Nutricion Mineral-CIHNM, Lima, Peru. With permission.)

FIGURE 15.29 Lettuces in NFT 3-in. pipe A-frame, chard on right. (From Centro Investigacion Hidroponia y Nutricion Mineral-CIHNM, Lima, Peru. With permission.)

FIGURE 15.30 Various 3-in. pipe NFT systems on A-frames and bench. (From Centro Investigacion Hidroponia y Nutricion Mineral-CIHNM, Lima, Peru. With permission.)

FIGURE 15.31 Bibb lettuce growing in pipe NFT system. (From Invernaderos Hidroponicos del Peru, SAC, Lurin, Lima, Peru. With permission.)

FIGURE 15.32 Lettuce growing in PVC pipe NFT system. Note: Left is inlet end, right is drain-return end to catchment pipe. (From Invernaderos Hidroponicos del Peru, SAC, Lurin, Lima, Peru. With permission.)

FIGURE 15.33 NFT A-frame. Note: The cistern nutrient tank in foreground. (From Invernaderos Hidroponicos del Peru, SAC, Lurin, Lima, Peru. With permission.)

FIGURE 15.34 Lettuce seedlings in propagation house. Seeds are sown in trays of sand. (From Invernaderos Hidroponicos del Peru, SAC, Lurin, Lima, Peru. With permission.)

Lettuce is seeded manually using coated seeds (pelletized) in coarse sand in 72-cell trays (Figures 15.34 and 15.35). It is transplanted 30 d after sowing. It can be harvested from 28 to 40 d after transplanting depending on the season. During winter it takes up to 40 d as day length is short and there is a lot of cloud and fog during the winter from July through September. The sand is not reused after each crop. Pipes and trays are cleaned with sodium hypochlorite solution.

Two houses grow spinach in sand culture with hoses of drip irrigation. The seed is directly sown into the sand beds (Figure 15.36). The crop is harvested as leaves only, so the plants are cut about 30–35 d after seeding (Figure 15.37).

Tomatoes, cucumbers, peppers and eggplants are grown in slabs of sand (Figure 15.38). They are trained vertically and lowered as they approach the above support wire.

All produce is sold to supermarkets in Peru, such as Wong, Metro, and Supermercados Peruanos. Some cherry tomatoes are exported to Canada and lettuce to Miami, Florida, USA.

The success of this operation is a result of good management and expansion with the market as it develops with the increasing middle class of people, who can be more selective in their demands for high-quality produce. The CIHNM at the Universidad de La Molina can be credited for introducing hydroponic culture to Peru and other areas of South America.

15.7 SPECIAL APPLICATIONS

15.7.1 Hydroponics and Resorts and Spas

A unique concept is the combination of a hotel resort complex with a hydroponic greenhouse farm. In the Caribbean, and the South Pacific islands it may be difficult to obtain good-quality fresh vegetables. Many of these more isolated, popular tourist locations are in areas of limited agricultural production. On many of the islands, food must be shipped into the countries by air or sea. Fresh, perishable, salad crops, such as tomatoes, cucumbers, peppers, lettuce, herbs, and related products are limited or not available.

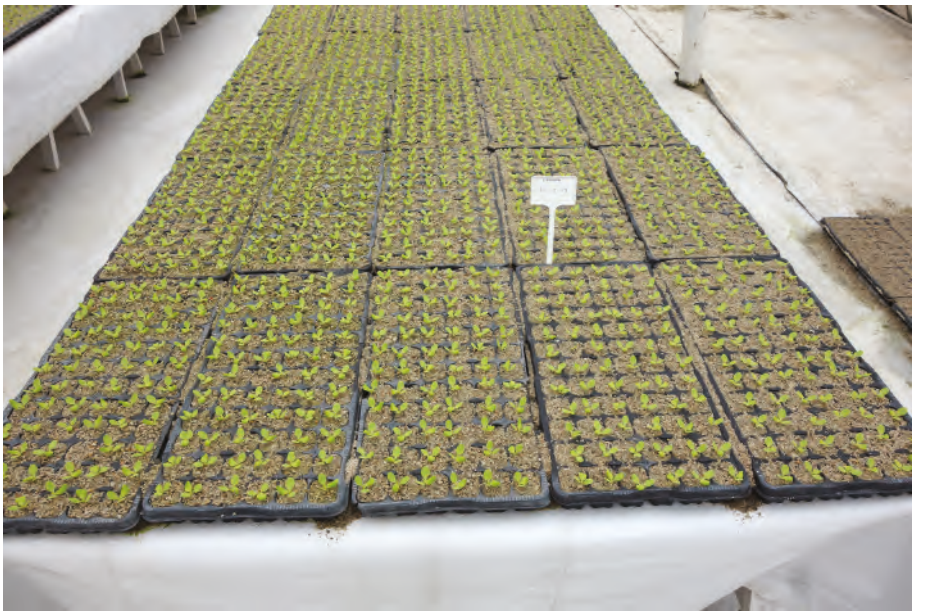

FIGURE 15.35 Lettuce seedlings in trays of coarse sand at 14 d. (From Invernaderos Hidroponicos del Peru, SAC, Lurin, Lima, Peru. With permission.)

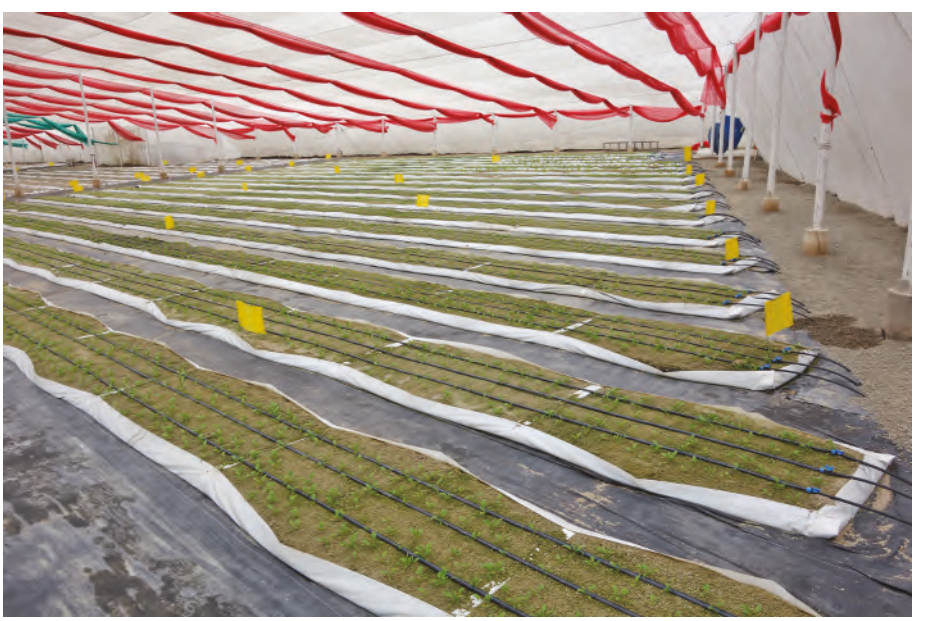

FIGURE 15.36 Spinach sown directly in sand with drip hoses. (From Invernaderos Hidroponicos del Peru, SAC, Lurin, Lima, Peru. With permission.)

FIGURE 15.37 Spinach ready to harvest as leaves at 32–35 d. Note: Yellow sticky insect traps. (From Invernaderos Hidroponicos del Peru, SAC, Lurin, Lima, Peru. With permission.)

FIGURE 15.38 Eggplants growing in sand slabs. Note: The stems are bent and laid down on top of the slabs as the plants are lowered. (From Invernaderos Hidroponicos del Peru, SAC, Lurin, Lima, Peru. With permission.)

Hydroponic farms also play a significant role in the operation of health spas associated with such resorts, as is the case with CuisinArt Golf Resort & Spa in Anguilla, British West Indies. The fresh vegetables can be a part of a "wellness" program provided by the spa. Travelers are becoming increasingly aware of the source and quality of the foods eaten in these regions. They realize a sense of security in eating fresh salad crops when they are produced at the site of the resort. To further assist their confidence, the hydroponic farms can offer tours to the resort guests. The guests will even more appreciate their salads once they learn how they have been grown at the resort. In many other regions, such as Mexico and Central America, tourists often experience sickness related to unclean salad crops. This can be avoided by growing the salad crops on-site in a hydroponic farm.

In most areas, a lightweight greenhouse structure can be constructed of polyethylene with shade cover on a galvanized steel tubular frame. These have little, if any, environmental control apart from protection against rain and pests. Alternatively, retractable roof structures may be used as described earlier.

With an eminent hurricane approaching, the covers and internal components (including all plants) are removed. While the covers and growing systems may be stored safely in a sturdy shed or container, all the plants will have to be harvested or removed. Such practice stalls production from the first hurricane until the end of the season in November. If the first hurricane arrives early in the season, such as August or September, production is curtailed from then until the end of November when it is safe to assume that a further one will not occur that season. It will take several months after that to get a new crop into production. So, in reality the season could be as short as 6–7 mo a year. Of course, during some years certain islands will be spared from a hurricane, but that is a gamble. The result is that the local market cannot depend on fresh vegetable products year-round from such "greenhouse" hydroponic operations.

In areas prone to hurricanes of winds of 150 mph (250 kph) or greater, special heavy, completely enclosed structures are needed to withstand such conditions. This alternative is to build a "hurricane-proof" greenhouse. That was the case with CuisinArt Golf Resort & Spa in Anguilla (Figure 15.39), a unique concept of a hotel combined with a hydroponic greenhouse. The greenhouse is an integral

FIGURE 15.39 CuisinArt Golf Resort & Spa hydroponic farm. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

part of the hotel complex in providing fresh salads for its restaurants. It is imperative that the greenhouse will withstand hurricanes. Crops cannot be interrupted by such weather phenomena.

A special greenhouse was engineered to withstand hurricane winds up to 150 mph, so that the crops scheduled to be bearing could be protected during the hurricane season. The greenhouse constructed by AgraTech Greenhouse Manufacturing of Pittsburg, California, proved its resilience during numerous hurricanes that have occurred over the past years. To withstand such hurricane winds, the greenhouse superstructure has twice the number of galvanized steel members as a normal greenhouse constructed under North American or European standards. Posts and trusses are located at 6-ft (1.8-m) centers. The structure is set into a perimeter concrete footing and foundation 18 in (46-cm) wide by over 3 ft (1 m) deep. The roof and sidewalls are covered with corrugated polycarbonate plastic, a very durable material. Each valley of the corrugations is screwed to the purlins running horizontally along the roof across the trusses. The polycarbonate plastic corrugated roof panels resist such strong winds and have stood up to the high ultraviolet light conditions of the tropics over the past years with little loss of light transmission. Roof vents, cooling pads, and exhaust fans regulate temperatures. As long as the relative humidity in these regions is from 55–75%, cooling is possible. This cooling is fairly efficient during the winter months from December through March when humidity levels are lowest.

The CuisinArt Hydroponic Farm greenhouse is 18,000 ft^2 (1,673 m^2) in area. A number of hydroponic systems are used, including perlite bato buckets, raft culture, vertical plant towers, and raised beds with a peat-lite substrate. Crops grown include tomatoes, peppers, European cucumbers, eggplants, Bibb and other lettuces, bok choy, arugula, herbs, and microgreens as described in Chapters 5 and 13. This diversification is to meet the hotel's fresh salad requirements. In this small greenhouse annual production (2009–2010) was as shown in the following table.

Tomatoes (beefsteak, cherry, roma)	13,037 lb
Peppers (red, orange, yellow)	5,568 lb
European Cucumbers	5,018 lb
Persian (Japanese) Cucumbers	1,727 lb
Bibb (European) Lettuce	23,280 heads
Other Novelty Lettuce	15,275 heads
Eggplants	650 lb
Bok Choy	3,600 heads
Arugula	564 lb.
Herbs	1,005 lbs.

The main area of the greenhouse growing tomatoes, cucumbers, and peppers in bato buckets of perlite contained 1,382 tomato, 109 cucumber, and 692 pepper plants. In addition, herbs, bok choy, and watercress are grown in a series of 66 plant towers located around the perimeter walls of two sides of the greenhouse. Two lettuce ponds, as described in Chapter 5, house 3,328 heads of European Bibb lettuce. The other novelty lettuces, arugula, and basils are grown in raised beds of a total area of 2,200 ft^2 (200 m^2).

Hydroponics can be part of tourist attractions such as Epcot Center and the Biosphere. It can be incorporated into theme parks and wellness spas and retreats. It is beneficial to the hotel resorts located in areas of nonarable lands and limited sources of fresh water where desalination of sea water can be used with hydroponic culture.

15.7.2 Hydroponic Rooftop Greenhouses

The idea of rooftop gardens has been in use for several decades, but they normally are outside gardens of simple beds or pots with ornamentals or vegetables. Today, there is more focus on the use

of hydroponics and greenhouses to produce vegetable crops commercially. The author was first exposed to this concept in 1986 in Taipei, Taiwan, where an investor wanted to erect a hydroponic greenhouse farm on top of a 13-storey apartment building in the middle of Taipei. The engineering was done and the erection of the greenhouse was started, but the project had to be stopped because of the wishes of the apartment owners, as they walked their dogs and exercised on the roof of the building.

15.7.2.1 Lufa Farms

The idea reemerged in 2009 with the founding of Lufa Farms in Montreal, Quebec, Canada. In 2011, Lufa Farms started production of the world's first commercial rooftop greenhouse in downtown Montreal, Quebec, Canada (Lunau, 2010). A 31,000 ft^2 (2,881 m^2) facility was constructed on the top of a two-storey warehouse (Figure 15.40). The author was involved in this project at the early stage of Lufa Farm's birth to oversee the design and development of this multicrop greenhouse and coordinated the startup with Lauren Rathmell, who supervised the establishment of the first crop. Of course, to do such a project requires a building constructed strong enough to meet city building codes of adding the weight of the greenhouse on the roof.

The greenhouse is a modern, up-to-date glass structure with central hot water heating, high-intensity discharge (HID) lights, CO_2 enrichment, shade/insulation curtains, Argus computer controller, and injection system. The plan is to grow greenhouse vegetable crops year-round. Crops grown include tomatoes, peppers, cucumbers, eggplants, lettuce, herbs, salad mixes, bok choy, and microgreens.

The greenhouse has two heating zones. There is a cool zone for the lettuce, bok choy, basils, herbs, salad mixes, and microgreens. Lettuce, basils, chard, arugula, bok choy, and some herbs are grown in a NFT system by American Hydroponics (www.amhydro.com). The salad mixes and microgreens are grown in an ebb-and-flood system. The cool zone has evaporative cooling pads and

FIGURE 15.40 Rooftop hydroponic greenhouse in downtown Montreal, Canada. (From Lufa Farms, Montreal, Canada. With permission.)

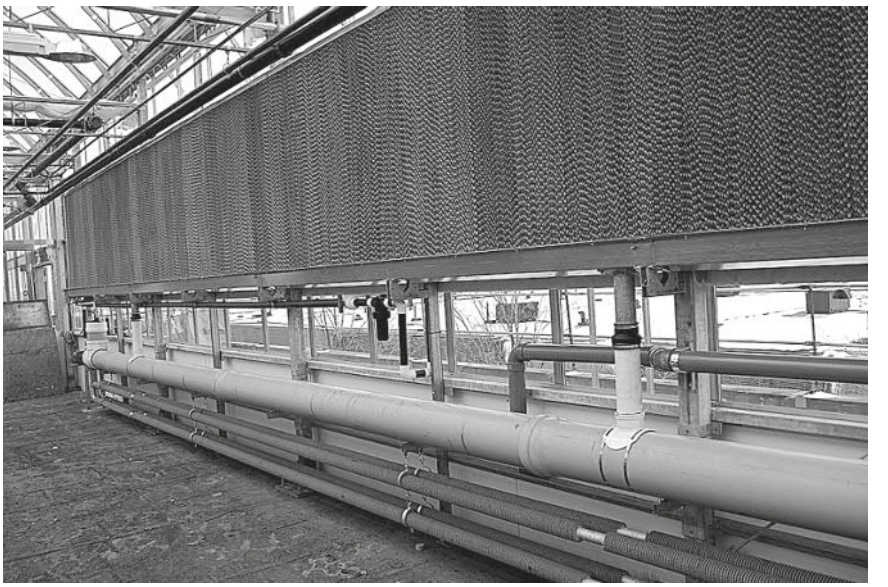

FIGURE 15.41 Evaporative cooling pad. Note: The radial fin heating pipes below the cooling pad collection pipe. (From Lufa Farms, Montreal, Canada. With permission.)

exhaust fans (Figures 15.41 and 15.42). The greenhouse and heating system were designed and built by Westbrook Greenhouse Systems Ltd. of Beamsville, Ontario, Canada (www.westbrooksystems.com). All of the heating system functions from three hot water boilers located in the greenhouse with hot water pipe distribution (Figure 15.43). Heating pipes include perimeter wall heating, floor heating pipes in the warm zone, and overhead heating in the cool zone.

The warm heating zone is for the other section of the greenhouse that is growing tomatoes, peppers, cucumbers, eggplants, and other warm-season herbs. The two zones are separated by a glass partition wall. The vine crops are grown in FormFlex raised trays using coco coir slabs (Refer to Chapters 10 and 11). The greenhouse has CO_2 enrichment in both sections and a full array of HID lighting to enable the growing of these crops year-round.

The recent greenhouses have a larger central boiler as shown in Figure 15.44 for the Ville Saint-Laurent greenhouse growing tomatoes and eggplants.

The tomatoes, peppers, eggplants, and cucumbers were started by a contract nursery propagator. The tomatoes, peppers, and eggplants were grafted to a disease resistant rootstock. The seedlings are normally grown in the nursery for 55 d, but the first crop had to be extended to 65 d because the construction was several weeks behind schedule. These seedlings were transplanted directly to the coco coir slabs at the 65th day.

Within several weeks of transplanting the plants grow vigorously as the roots enter the coco coir slabs (Figures 15.45 and 15.46). The seedlings were started in rockwool blocks and transplanted 65 d after sowing.

Owing to the diversity of the crops grown, several nutrient systems were designed to enable the use of separate nutrient formulations. All of the leachate is recycled to the fertigation system located in the basement (underground parking) of the building. The leachate is collected in the return tanks where it is filtered to remove any particulate matter and pasteurized by hydrogen peroxide before going to the premix batch tanks where the *p*H and EC are adjusted by a loop through the injector systems. There are separate injectors for each premix tank. After adjustment that is regulated by the computer controller, the solution is pumped back to the greenhouse irrigation system on the roof.

FIGURE 15.42 Exhaust fans on the side opposite to the cooling pad. (From Lufa Farms, Montreal, Canada. With permission.)

FIGURE 15.43 Hot water boilers for heating system. (From Lufa Farms, Montreal, Canada. With permission.)

Any loss of water by evapotranspiration of the plants is made up by adding raw water from supply tanks to the batch tanks before solution adjustment by the injectors.

It is very complicated to design these independent nutritional systems for the different crops when growing many types of crops together. In such a case, the formulation for a specific crop may not be the most optimum, but often some formulations for specific crops may not differ significantly.

FIGURE 15.44 Larger boiler used in Ville Saint-Laurent greenhouse. From Lufa Farms, Montreal, Canada. With permission.)

FIGURE 15.45 Eggplants and peppers 2 wk after transplanting. Note: The shade curtains above are drawn to reduce the light during the rooting process. (From Lufa Farms, Montreal, Canada. With permission.)

FIGURE 15.46 Peppers on coco coir slabs on FormFlex raised trays. (From Lufa Farms, Montreal, Canada. With permission.)

All crops are grown free of synthetic chemical pesticides by using beneficial insects and biological agents, which are natural pesticides. The products are sold as "pesticide free."

Marketing of the product is by "subscribers," whom they call "Lufavores." People join as members to receive a basket of fresh produce weekly. They order a weekly customized basket with a fresh mix of vegetables that includes tomatoes, peppers, eggplants, cucumbers, lettuce, salad mixes, arugula, herbs, and other products. By 2020 they have expanded these basket mixes to about 50 varieties of vegetables from Lufa's rooftop greenhouses; to a selection of other fruits and vegetables from about 150 partner farmers and foodmakers. They claim to deliver about 20,000 baskets weekly to 350 pick-up points across Montreal and Quebec City. In selected cities home delivery is also available.

They have in 2020 four rooftop greenhouses with a total growing area of 300,000 ft^2 (27,900 m^2) employing about 500 people. They harvest weekly over 56,000 lb (25,500 kg) of vegetables from the greenhouses. The first rooftop greenhouse, the Ahuntsic, shown in Figure 15.40 was built in 2011 at 31,000 ft^2 (2,880 m^2). That greenhouse grows herbs, microgreens, and peppers. Lufa Farms expansion over the following years includes the following rooftop greenhouse operations:

1. Laval (2013) with an area of 43,000 ft^2 (3,995 m^2) growing cucumbers (Figure 15.47).
2. Anjou (2017) having an area of 63,000 ft^2 (5,853 m^2) with crops of lettuce, herbs, leafy greens (Figure 15.48).
3. Ville Saint-Laurent (2020) 163,800 ft^2 (15,218 m^2) in size growing tomatoes and eggplants. This greenhouse is shown in Figures 15.49 and 15.50. This rooftop greenhouse is located on top of a former Sears warehouse.

FIGURE 15.47 Laval greenhouse of 43,000 ft^2 growing cucumbers. (From Lufa Farms, Montreal, Canada. With permission.)

FIGURE 15.48 Anjou greenhouse of 63,000 ft^2 with lettuce, herbs, and leafy greens. (From Lufa Farms, Montreal, Canada. With permission.)

FIGURE 15.49 Lufa Farms 163,800 ft^2 rooftop greenhouse at Ville Saint-Laurent, Quebec, Canada. (From Lufa Farms, Montreal, Canada. With permission.)

FIGURE 15.50 Tomatoes in 163,800 ft^2 rooftop greenhouse at Ville Saint-Laurent, Quebec, Canada. (From Lufa Farms, Montreal, Canada. With permission.)

All of the rooftop greenhouses are located in the Montreal region. They deliver to pick-up points within a 3 h radius of Montreal.

With success at these sites, it is anticipated to construct more rooftop hydroponic greenhouse gardens in the city centers of large population areas on the northeast coast of Canada and the United States, where fresh produce often is not readily available, especially during the winter months. In milder climates in the western part of North America, this concept is probably not as feasible, especially when there is usually an abundance of fresh produce from California. Similar application in Europe may be feasible in cities of England, Germany, and northern countries. There, fresh produce in winter would come from Spain, so countries near Spain may have adequate product available during winter, and therefore a rooftop garden in those southern countries probably would not be economically feasible.

15.7.2.2 Gotham Greens

Another similar rooftop hydroponic greenhouse was established in 2011 by Gotham Greens on a two-story industrial building in Greenpoint, Brooklyn, New York City. It has a solar array of panels that generates 55 kW of electricity to assist in the electrical needs of the greenhouse (Figure 15.51).

The greenhouse is 15,000 ft^2 (1,394 m^2) in area (Figure 15.52). It is constructed of galvanized steel, aluminum, and double-wall polycarbonate. Components include natural ventilation, shade curtains, unit heaters, and high pressure sodium (HPS) lighting.

Gotham Greens grows lettuce with a moveable NFT recirculating system (Figure 15.53).

The concept is certainly the way of the future in providing large population centers with fresh produce year-round. With the rising costs of fuel for transportation and innovations of highly efficient artificial lighting, the economic feasibility of rooftop hydroponic greenhouses on the largely idle roofs will become more common.

Over the past decade since the construction of its first rooftop greenhouse, Gotham Greens has expanded in other areas of the United States with rooftop greenhouses and ground-level greenhouses

FIGURE 15.51 Gotham Greens greenhouse with solar array. (From Ari Burling & Gotham Greens, Brooklyn, NY. With permission.)

FIGURE 15.52 Gotham Greens 15,000 ft^2 greenhouse in Brooklyn, New York. (From Ari Burling & Gotham Greens, Brooklyn, NY. With permission.)

FIGURE 15.53 Gotham Greens growing lettuce in moveable NFT. (From Gotham Greens, Providence RI. With permission.)

FIGURE 15.54 Gotham Greens rooftop greenhouse on a Whole Foods Market, Brooklyn, New York. (From Gotham Greens, Brooklyn, NY. With permission.)

FIGURE 15.55 Gotham Greens 75,000 ft^2 rooftop greenhouse in Chicago's Pullman Historic Neighborhood. (From Gotham Greens and Julie McMahon, Chicago IL. With permission.)

located near large population centers. In 2013, Gotham Greens completed a rooftop greenhouse of 20,000 ft^2 on top of a Whole Foods Market, in the Brooklyn neighborhood of Gowanus, New York City (Figure 15.54). This project is an exhibit to educate the public in the latest energy efficient growing of lettuce and herbs.

In 2015, Gotham Greens expanded to Chicago, Illinois, with a 75,000 ft^2 greenhouse on top of Methods Products manufacturing plant (Figure 15.55). The facility grows millions of heads of leafy greens and herbs annually for retailers and restaurants across greater Chicago and the Midwest. A 60,000 ft^2 facility in Jamaica, Queens in New York City on the rooftop of the former Ideal Toy

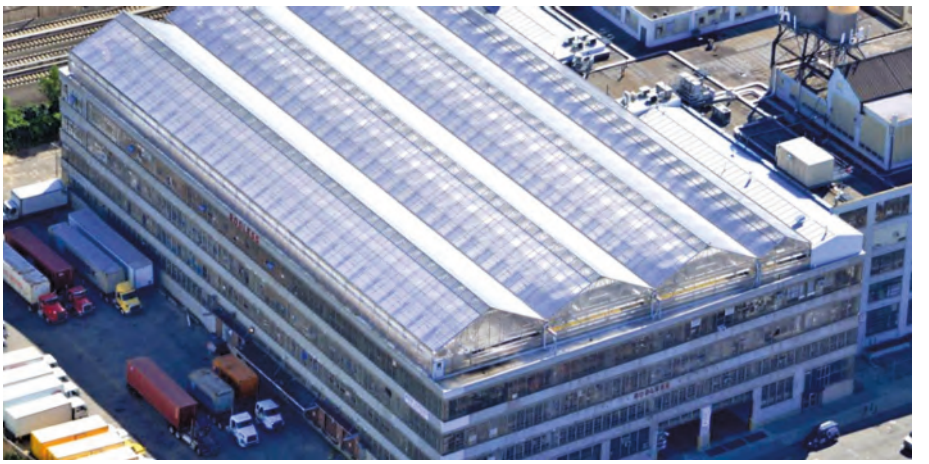

FIGURE 15.56 Gotham Greens 60,000 ft^2 rooftop greenhouse in Jamaica, Queens, New York. (From Gotham Greens, Brooklyn, NY. With permission.)

FIGURE 15.57 Gotham Greens ground level greenhouse of 100,000 ft^2 in Providence, Rhode Island. (From Gotham Greens, Providence, RI. With permission.)

Company factory also opened in 2015 producing millions of heads of leafy green each year for the New York Tri-State area (Figures 15.56).

In 2019, Gotham Greens opened three 100,000 ft^2 greenhouses in Chicago, Illinois, Providence, Rhode Island, and Baltimore, Maryland. These are not rooftop greenhouses but rather conventional greenhouses located near large population centers (Figures 15.57 through 15.59).

Gotham Greens continues to expand with the most recent greenhouse (2021) now in operation in Denver, Colorado. Today, the company operates 500,000 ft^2 of greenhouse across five US states. In 2021, Gotham Greens announced the first phase of a 10-acre (4-ha) greenhouse facility to be constructed near the University of California-Davis (UC Davis). The new facility will enable Gotham Greens and the University of California to collaborate on research and innovation in indoor agriculture in addition to being a commercial operation of leafy greens to supply the West Coast market. Gotham Greens products are available in more than 2,000 retail stores, including Whole Foods Market, Albertsons Companies, Meijer, Target, King Soopers, Harris

FIGURE 15.58 Gotham Greens greenhouse of 100,000 ft^2 in Chicago, Illinois. (From Gotham Greens and Robo Aerial, Chicago, Il. With permission.)

FIGURE 15.59 Gotham Greens 100,000 ft^2 ground level greenhouse in Providence, Rhode Island with basil. (From Gotham Greens and Julie McMahon, Providence, RI. With permission.)

FIGURE 15.60 Hydroponic greenhouse on the Science Barge. (From Manuela Zamora & New York Sun Works, New York, NY. With permission.)

Teeter, ShopRite, and Sprouts, as well as grocery e-commerce sites, and independent and natural grocery stores.

15.7.3 The Science Barge

The Science Barge is a sustainable urban farm designed by New York Sun Works (www.nysunworks.org). The floating barge contains a hydroponic greenhouse powered by solar, wind, and biofuels that grows tomatoes, cucumbers, peppers, lettuce, and herbs. Biofuels include biodiesel and waste vegetable oil. Biofuels are made from food industry by-products. The Cornell Cooperative Extension, New York City, stated in 2005 that New York City restaurants generate sufficient waste oil to supply 10 million gallons of biodiesel fuel annually. The Science Barge tours New York City's public waterfront parks (Figure 15.60). It is a demonstration of renewable energy supporting sustainable vegetable production using rainwater and river water purified by reverse osmosis (RO) for irrigation of the crops. They have a public education program with school groups and the general public.

15.7.4 New York Sun Works

In 2010, New York Sun Works, a non-profit organization, opened the Sun Works Center for Environmental Studies at the Manhattan School for Children (Figure 15.61). This is a rooftop greenhouse that functions as a practical classroom on integrated environmental studies offered to students from kindergarten through eighth grade (Figure 15.62) (MacDonald, 2010; MacIsaac, 2010). New York Sun Works wishes to build 100 of these rooftop greenhouse classrooms throughout New York City.

New York Sun Work's *Greenhouse Project* is dedicated to improving Environmental Science Education in urban schools. The *Greenhouse Classroom Labs* instruct students to grow food hydroponically. They state, "Our Greenhouse Classroom Labs offer students the opportunity to grow food, while learning hands-on about nutrition, water resource management, efficient land use, climate change, biodiversity, conservation, contamination, pollution, waste management, and sustainable

FIGURE 15.61 Rooftop hydroponic greenhouse at the Manhattan School for Children. (From New York Sun Works, New York, NY. With permission.)

FIGURE 15.62 School classroom rooftop hydroponic greenhouse. (From Manuela Zamora & New York Sun Works, New York, NY. With permission.)

development." The *Greenhouse Project* lab can include solar panels, hydroponic growing systems, aquaculture, rainwater collection, weather station, and integrated pest management (IPM).

New York Sun Works offers *Home Hydroponic Kits* that enable students, with teacher assistance, to grow and study plants from home or in classroom. The objective of New York Sun Work's

Greenhouse Project curriculum is to introduce students to cutting-edge technology and through sustainable urban farming, connect science and the environment.

New York Sun Works was founded by Dr. Ted Caplow in 2004 after creating the Science Barge. The first Greenhouse Project Lab was completed in 2010, as shown in Figures 15.61 and 15.62. By 2020, they have expanded to 129 labs, have trained 450 teachers and have reached 40,000 students. They connect with communities through cooking demonstrations, farm stands, and harvest celebrations. New York Sun Works is a non-profit organization that takes donations and has annual community events.

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16 Plant Culture

16.1 INTRODUCTION

While this book is an outline and review of soilless culture methods, it is appropriate to discuss briefly some of the methods and products available for the growing of seedlings to be transplanted into a soilless culture system. In order to successfully grow plants, one must start out with vigorous and healthy disease-free seedlings. We shall then proceed to other aspects of successful plant cultures.

16.2 SEEDING

All plants for hydroponic culture should be started from seeds. Some growers may wish to purchase seedlings ready to transplant from specialized transplant growers such as Bevo Agro, mentioned in Chapter 6. Tomato seedlings are 6 wk old, cucumber seedlings 4 wk and pepper seedlings 8 wk on delivery. However, such a transplanting method using purchased plants is really most applicable to North America or Europe where shipping can be done by ground transportation within several days. The risk of using transplants grown by someone else is that they could have a disease that would be transmitted throughout your crop. However, most propagators practice very stringent sanitation methods. In addition, with grafting becoming the acceptable method of growing most cultivars of tomatoes, peppers, and eggplants, it is much easier to have a specialized propagator do this as most growers are not set up or do not have trained people to do the green grafting. In areas of high sunlight conditions such as desert and tropical regions it is possible to transplant seedlings at an earlier stage. In those locations, it may be beneficial and cheaper to raise your own seedlings. Cucumbers, for instance, in tropical regions such as Florida and Anguilla can be transplanted at 10–14 d from sowing since they grow very rapidly under the high sunlight of those areas.

A number of methods for sowing seeds are available. One may seed directly into multi-pack trays using a peat-lite mix or any other suitable substrate as perlite, vermiculite, or granular rockwool. Many types of containers are on the market. Plastic "com-packs" and "multi-pots" are shaped like ice-cube trays with one large compartment to 12 compartments per pack (5.25 in. x 5.25 in. x 2.31 in. deep) (13 cm x 13 cm x 6 cm) (Figure 16.1). These come in 89 packs per 10.5 in. x 21 in. (27 cm x 53 cm) sheet, which fits into a corresponding plastic flat. A similar product (Jiffy strips) is made of peat rather than plastic. In addition, individual plastic and peat pots of various sizes are available. In all of these containers a soilless mix must be used. Most vegetable plants can be grown satisfactorily in 2.25- or 3-in. (5- or 8-cm) square or round pots. In the peat pots and strips, transplanting is done by placing the pot and medium into the beds. The plant roots will grow through the peat container walls.

An alternative method is to seed directly into Jiffy peat pellets, Oasis "Horticubes," rockwool cubes, or coco coir cubes. Seeds are placed in small precut seeding holes. Peat pellets are compressed peat discs contained by a nylon mesh. These discs are about 1.5 in. (4 cm) in diameter and 0.25 in. (0.6 cm) thick when shipped dry. After soaking in water for 5–10 min they swell to about 1.5 in. (4 cm) in height (Figure 16.1). Seeds are placed in the top and may be covered with their peat medium. They contain sufficient nutrients to carry most plants for 3–4 wk. Plant roots grow out through the nylon mesh. During transplanting, the peat pellet (Jiffy-7) with the plant is placed in the growing bed.

DOI: 10.1201/9781003133254-16

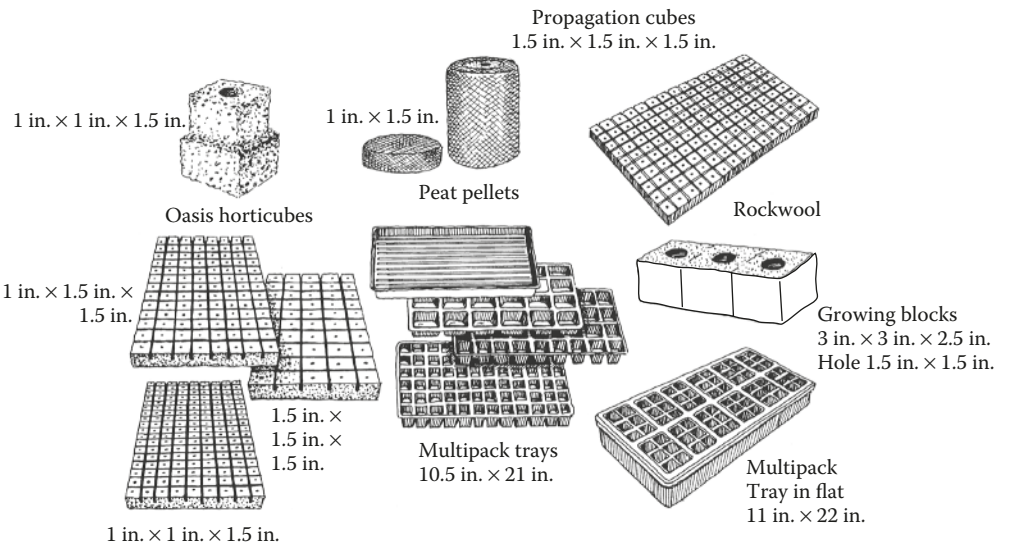
Propagation cubes
1.5 in. × 1.5 in. × 1.5 in.
1 in. × 1 in. × 1.5 in.
1 in. × 1.5 in.
Peat pellets
Rockwool
Oasis horticubes
1 in. × 1.5 in. ×
1.5 in.
Growing blocks
3 in. × 3 in. × 2.5 in.
Hole 1.5 in. × 1.5 in.
1.5 in. ×
1.5 in. ×
1.5 in.
Multipack trays
10.5 in. × 21 in.
Multipack
Tray in flat
11 in. × 22 in.
1 in. × 1 in. × 1.5 in.

FIGURE 16.1 Seedling propagation cubes, blocks, peat-pellets, and trays. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

Oasis cubes, rockwool cubes and blocks, and coco coir cubes and blocks are commonly used with nutrient film technique (NFT), rockwool, perlite, coco coir, and sawdust cultures. Use of rockwool blocks originated in Denmark, Holland, and Sweden. They are the most widely used form of growing blocks for tomatoes, cucumbers, peppers, and eggplants. Coco coir cubes and blocks have been introduced and it is expected that they will gain market share as more coco coir hydroponic systems are employed.

Rockwool is composed of coke and limestone molten at 1,600°C (2,923°F) and spun into fibers. The fibers are woven into slabs, stabilized with phenolic resin, and provided with a wetting agent. The most widely used rockwool block is manufactured under the trade mark "Grodan." Other manufacturers of rockwool products now exist in North America, Europe, and Japan.

Chemically, rockwool blocks are relatively inert as the elements they contain are practically unavailable to plants. While they are slightly alkaline in *p*H, they are quickly neutralized after a short time of passing nutrient solutions of lower *p*H through them.

Rockwool blocks have good physical properties of low volume weight, a large pore volume, and a great water-retention capacity. Both rockwool cubes and Oasis cubes are often used with NFT systems. Both these growing blocks are sterile, so that disinfecting measures are unnecessary.

Rockwool cubes/blocks are available as propagation cubes and growing blocks. The propagation cubes come in several sizes. Small cubes of 200 per standard flat dimension measure 1 in. x 1 in. x 1.5 in. high (2.5 cm x 2.5 cm x 4 cm), which are most suitable for lettuce and herbs. Larger cubes of 98 per tray that measure 1.5 in. x 1.5 in. x 1.5 in. (4 cm x 4 cm x 4cm) are best for tomatoes, peppers, cucumbers, and eggplants (vine crops). The propagation cubes have small holes of approximately 0.25 in. (0.6 cm) round and deep for the placement of seeds. Seeds are sown in propagation cubes, which in turn are placed into growing blocks after several weeks of growth. This "pot-in-pot" system permits seedlings to continue growing in the same medium with a minimum of transplanting shock. This does not apply to lettuce and herbs, which are transplanted directly from the propagation cubes into the final production culture.

Growing blocks are wrapped around the perimeter in polyethylene and come in a number of sizes. The most common ones used for vine crops in hydroponics are 3 in. (7.5 cm) and 4 in. (10 cm)

square by 2.5 in. (6 cm) deep. There are also tall blocks of almost 4 in. (10 cm) in depth for vigorous crops as cucumbers and melons or for carrying seedlings to a later stage before transplanting. Now, many growers also use double blocks (Grodan Plantop Delta) (Figure 10.24) as described in Section 10.8 to grow 2 plants per double block. The holes in these blocks are round, of 1.5 in. diameter and 1.5 in. depth (4 cm x 4 cm) to fit the larger propagation cubes of 1.5 in. (4 cm) dimensions

With most commercial growers purchasing grafted plants from propagators, Grodan has developed special rockwool plugs that fit individually into Grodan Kiem Plug Trays to facilitate automatic seeding, as these propagators sow thousands of seeds at a time. The Kiem plug trays have 240 plugs in each tray. These trays can be placed in ebb-and-flood propagation tables for high-density propagation. After germination, the seedlings can be transplanted to NFT channels or moved on into the larger blocks for growing on.

The Grodan plugs are 2.0 cm in diameter by 2.5 cm in height (0.8 in. x 1 in.). They have several hole configurations of 0.75 cm (0.3 in.) depth that have sloped sides to permit seeds to enter without missing when using automatic seeders. In addition, the sloped sides permit covering of the seeds with vermiculite, which can be added automatically following the sowing. The round plugs fit easily into rockwool cubes having round holes of similar diameter.

Rockwool cubes and blocks must be thoroughly moistened before seeding or transplanting. If not, dry spots will restrict root growth within them. Similarly, Oasis cubes, coco cubes and blocks, and peat pellets must be saturated with water before seeding. This can be accomplished in several ways: overhead sprinkling for 1 h, soaking through hand submersion, or by overhead boom irrigators until the cubes are completely saturated. Seeds can then be placed in the pre-punched hole in each cube. When roots appear on the outside of the cubes and true leaves develop, the plants are ready for transplanting. Since the plants are transplanted intact with their cubes, a minimum of transplant setback occurs.

Oasis "Horticubes" are widely used in North America specifically for hydroponic and NFT applications. These cubes have good drainage, making them ideal for seed germination. The "Horticubes" medium is available in 1 in. x 1 in. x 1.5 in. (2.5 cm x 2.5 cm x 3.8 cm) cubes for maximum planting density. Each medium tray is composed of 162 cubes joined at their bases to allow easy separation for transplanting. Their main advantages are that they are sterile, easy to handle, and have a balanced *p*H.

Sow one seed per propagation cube. Purchase new seed for each crop. Purchase only enough to allow some "overseeding." Pay attention to the percentage germination given on the seed package. From this rating calculate how much extra seed must be sown to meet the crop needs. For example, if the germination is 90%, one must sow 100/90 = 1.11 times the seeds to meet the plant numbers. That is 11% of additional seeds need to be sown in the propagation cubes. At the same time, some seeds will germinate poorly, giving weak seedlings. Add another 5% to compensate for these plants. Large seeds germinate more uniformly. Cucumbers seeds are very expensive, so do not sow more than what is necessary to compensate for the germination percentage.

16.3 SEEDLING PRODUCTION

A basic rule in growing seedlings is, "A good seedling gives good production." The potential production of a plant is set early in its life cycle. A thin, spindly seedling will restrict flow of water and nutrients to the plant as it grows because of its thin stem base. Production will be reduced from what it is genetically capable of under optimum environmental conditions. Weak, spindly seedlings are easily infected by disease and insects and subject to lodging (falling over). This principle applies to all plants.

During germination, the seed embryo is activated and grows using the stored food of the endosperm. Imbibition is the expansion of the seed as it absorbs water. Various biochemical processes take place to activate the embryo and break down the stored food (starch) to make it available to the

embryo for growth. Germination requires water, oxygen, specific temperatures, and light (or lack of it). The grower must provide these optimum conditions to permit the seed to germinate rapidly and begin manufacturing its own food through photosynthesis. Rapid, but not succulent, growth will produce a seedling resistant to diseases.

Sterilization of raw water and application of chemical or biological agent sprays can reduce disease infection. However, care must be exercised not to damage the tender seedlings. Use lower rates with applying such sprays to seedlings, and preferably do not do so until several sets of true leaves have formed. During the growing of seedlings, fungus gnats (Figure 16.77) become increasingly present as one starts to add a nutrient solution to the plants. This creates a moist nutrient-rich surface on the cubes, which quickly forms algae that is very favorable to fungus gnats. Fungus gnats lay eggs in the moist surface of the cubes, and larvae that hatch feed on plants' roots. One bioagent that can be used as a weekly soak to reduce the presence of the fungus gnat larvae is "Gnatrol," a biological larvicide. The active ingredient of Gnatrol is 37.4% *Bacillus thuringiensis*, subspecies *israelensis.* This is a beneficial bacterium available from Valent Biosciences Corporation.

Application rates for light infestation are 3.2–6.4 oz per 100 US gal, and for heavy infestations, 13–26 oz per 100 gal as a drench, that is, at 28.35 g/oz, 90.7–181 g or 368.5–737 g/378.5 L.

Use sterile growing trays, substrates, and propagation cubes. Prevent clean trays and cubes from being contaminated. Clean propagation benches before use with a 10% bleach solution. If plastic trays are to be reused, sterilize them for at least 0.5 h in 10% bleach solution.

16.3.1 Tomato Seedling Culture

The most common substrate is rockwool propagation cubes of 1.5 in. x 1.5 in. x 1.5 in. (4 cm x 4 cm x 4 cm). These cubes have good water retention yet are well drained to provide good oxygenation. They have a water to air ratio of 60–80%: 40–20%. Soak the cubes 1 d in advance with raw water of *p*H 5.5–6.0 and an EC of less than 0.5 mmho. After sowing the seeds into the preformed holes keep them moist, and then there is no need to cover the seeds. Water the cubes up to several times a day according to light and temperature conditions in the greenhouse. Do not allow them to dry out or to be excessively moist, as this will kill the germinating seeds.

Most commercial growers place the seeded cubes contained in trays in a special seedling section of the greenhouse. This area of the greenhouse has overhead sprinklers controlled intermittently from a time clock or moisture sensor. Overhead traveling boom irrigators, as used in the forest seedling industry, are particularly suitable to provide uniform watering. In this way, seedlings may be placed over the entire greenhouse area rather than leaving pathways for access by workers to manually water. Another method is to use ebb-and-flood benching. The watering cycles can be regulated by moisture sensors or an irrigation controller.

It is important that each watering soaks the medium thoroughly. Water should be applied uniformly over all plants, or uneven growth is likely to occur. Plants should be watered early enough so foliage will dry before dark. Remember that plants require less water during periods of dark, cloudy weather than during periods of bright, warm weather. As plants grow larger, they require more water. Normally, increasing day length and average temperature will increase water needs of plants.

Moveable, rolling benches or less expensive benching of concrete blocks, pipe, lumber, and wire mesh will serve as a temporary seedling area. In northern latitudes, the seedling area must have supplementary artificial lighting such as high-intensity discharge (HID) or LED lights to increase light intensity and daylength during winter months. After the seedlings have been transplanted to rockwool or other blocks, they should be kept in the seedling area until they reach about 55 d of age before transplanting to the growing section of the greenhouse. On this final transplanting, temporary benching can be removed and the area used also for production. As mentioned earlier, most growers prefer to purchase transplants at the 6- to 8- wk stage to avoid the labor and cost of raising their own seedlings. Furthermore, tomatoes are grafted to vigorous, disease-resistant rootstocks.

Green grafting is a tedious, labor-intensive process, so large growers should avoid it and purchase transplants. Green grafting is discussed in detail later in this chapter.

Drainage is very important during seedling growth. The water or nutrient solution must pass through the growing substrate and drain away from the plants. This provides adequate leaching and at the same time moves oxygen through the medium to the germinating seeds and their subsequent root formation. Do not set propagation cubes on plastic sheeting, as this will accumulate solution underneath the cubes, reducing available oxygen, and promote algae and subsequent fungus gnat infestation. Metal extruded mesh benches will provide good drainage and permit "root pruning" by air so that seedling roots will remain more in the cubes, forming a dense, well-branched root system. These roots will quickly grow into the slabs or other substrate in which the plants are finally placed.

Maintain temperatures from 77–79°F (25–26°C) during initial germination. As the seedlings emerge, the cotyledons expand (Figure 16.2). Increase the EC to 1.0–1.5 mmho in the form of a dilute nutrient solution. Lower the day temperature to 73°F (23°C) and night temperature to 68°F (20°C) over several days, and regulate these temperatures for several weeks.

In northerly regions with low levels of sunlight during the winter months, provide supplementary artificial lighting with the use of HID and/or LED lights. Check with lighting specialists and manufacturers as listed in Appendix 5 on the location of light fixtures, spacing, and so on, to obtain a daily light integral (DLI) of 13–16 mol/m^2/d over a 16–18 h/d photo period.

Procedures outlined here are most applicable to northerly regions of the United States, southern latitudes of Canada, and Europe where the conventional cropping period is from mid-December through mid-November. That is, seeds are sown in December and grown in a special seedling area of the greenhouse until being transplanted from late December to early January. During winter, day length is short and light intensity is very low. For this reason, supplementary lighting is imperative, and the use of high-EC nutrient solutions are practiced to slow vegetative growth, giving a sturdy plant.

Once the true leaves have fully unfolded (2–3 wk after sowing), transplant the cubes into 3 in. x 3 in. x 4 in. (7.5 cm x 7.5 cm x 10 cm) deep rockwool blocks. Larger blocks 4 in. x 4 in. x 3 in. (10 cm x 10 cm x 8 cm) are better if the seedlings are to be grown longer in the propagation area.

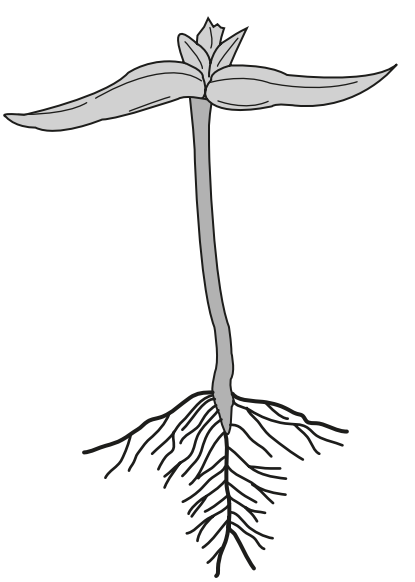

FIGURE 16.2 Seedling in cotyledon and early first-true-leaf stage. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 16.3 Transplanting tomatoes on side into rockwool blocks. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

The blocks should be thoroughly watered with a solution having an EC of 2.5–3.0 mmho and a *p*H of 6.0. For plants not grafted, invert the seedlings at 90° when placing them into the rockwool blocks (Figure 16.3). This procedure will strengthen the stems of seedlings, as adventitious roots will form on the buried part of the stems to increase roots, resulting in a stronger seedling. Stem breakage will be reduced by not watering the seedlings 24 h before transplanting. Space the blocks in a checkerboard pattern at 4–6 in. (10–15 cm), depending on the time before transplanting to the slabs or pots of the production area. If the plants are going to be held for 3–4 wk after this transfer to the blocks, space them at about five to six plants per flat (Figure 16.3). Many growers using rockwool or coco coir slabs transplant to double blocks (6 in. x 3 in. x 2.5 in. (15 cm x 7.5 cm x 6.5 cm) (length x width x height). Two seedlings are transplanted per double block. Each slab after transplanting will contain six plants that are trained in a V-cordon configuration strung alternatively to overhead support wires. Optimum temperatures during the day and night are 23°C (73°F) and 20°C (68°F), respectively. Maintain CO_2 levels between 500 and 700 ppm (mg/L).

A regular spray program to prevent diseases will assist the plants in becoming very healthy and prepared to cope with transplanting stress. Before transplanting to the slabs, use the beneficial microorganisms "Mycostop" or "RootShield" to prevent *Pythium* and *Fusarium* fungi infection. Hydrogen peroxide at 30–50 ppm in the nutrient solution will help reduce water-borne root rot diseases. Use good sanitation during transplanting. Transport all seedlings in sterilized trays and on sterilized equipment. Do not place them on the floor during transplanting, only directly on top of the slabs or other substrates. A healthy tomato transplant will be as wide as high with a thick, sturdy stem when it is transplanted (Figure 16.4).

16.3.2 Cucumber Seedling Culture

Similar to tomatoes, European cucumbers should be sown in 1.5 in. x 1.5 in. x 1.5 in. (4 cm x 4 cm x 4 cm) rockwool propagation cubes. However, as seeds are high in germination (usually 98%), they may be sown directly into rockwool blocks instead of using the cubes first and later transplanting to the blocks. But, by sowing in cubes first, the most vigorous seedlings can be selected for transplanting

FIGURE 16.4 Transplanting 5-wk-old tomato plants to perlite culture. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

to the blocks. The 4-in. square blocks with small holes 0.8 in. diameter x 0.6 in. depth (20 mm x 15 mm) are most suitable. Presoaking and subsequent watering procedures during germination to prevent drying must be adhered to as for tomatoes. Presoak the blocks thoroughly with water at 68–77°F (20–25°C), *p*H 5.5–6.0 and EC of 0.5 mmho.

In areas of high solar radiation, covering the seeds in the holes with some coarse vermiculite will prevent drying of the seeds. This practice will also assist in the shedding of the seed coats. Do not use fungicides during the early stages of germination, as they could slow germination, causing stunting of the seedlings. For both tomatoes and cucumbers, hydrogen peroxide may be used at 30 ppm on the seedlings and up to 50 ppm if algae are present.

Germinate the seeds at air temperatures of 75°F (24°C). They will germinate within 2 d. On germination, maintain the rockwool block temperature at 73°F (23°C) for the next 17 d. Air temperatures during the day should be 79°F (26°C) and at night 70°F (21°C).

In more northerly latitudes where sunlight is limited during winter months, increase the EC to 2.5–2.8 mmho after 7 d. Increase day length to 18 h using supplementary lighting similar to tomato seedlings. Refer to Chapter 12, Section 12.6 for detailed information on lighting. Regulate carbon dioxide levels between 700 and 800 ppm. As soon as leaves begin to overlap (within 10 d), space the blocks in a checker board fashion to reduce their density by half. This wider spacing will prevent the plants from growing tall and spindly, a condition that easily leads to disease infection. The seedlings may have to be spaced a second time if they are held beyond 3 wk and the leaves once again overlap.

If the seedlings are grown on wire mesh benches, the roots will be air pruned as they grow out of the blocks (Figure 16.5). As mentioned earlier, with tomatoes this forces the plants to form more roots within the blocks and reduces transplant shock as the roots can quickly grow into the slabs when transplanted.

Several days before transplanting, lower the seedling house temperatures to 72°F (22°C) during the day and 68°F (20°C) at night. Depending on seasonal sunlight and supplementary lighting used, an 18- to 28-d-old transplant should have three to four true leaves. In areas of high sunlight, the

FIGURE 16.5 European cucumber seedlings in rockwool blocks.

seedlings may be transplanted at an earlier stage. In Florida, we transplanted when seedlings had two leaves and the third was forming (Figure 16.5). In Anguilla, in the Caribbean, we transplanted at the two-leaf stage (about 14 d after sowing). In Anguilla, seeds were sown in rockwool cubes and transplanted to rockwool blocks at 5 d. Within 1 wk they root in and grow about 6 in. (15 cm) a day (Figure 16.6), and by 3 wk from transplanting to the buckets the plants start bearing fruit. They were kept bearing for 5–6 wk before being replaced with new plants to give a total crop cycle of 10–12 wk. Procedures must be changed somewhat to fit local environmental conditions and seasons due to day length differences.

As with tomatoes, drench the pots or slabs of substrate with "RootShield," a beneficial fungus, before transplanting to prevent *Pythium* and *Fusarium* infection. In addition, use hydrogen peroxide at 30–50 ppm in the nutrient solution to prevent water-borne fungi.

With a 10% bleach solution, sterilize all trays, wagons, and so on to transport the plants into the greenhouse production area. Place an emitter immediately on top of each block to irrigate using the ribbed stakes so that no solution will contact the plant stem, to avoid fungal infection. Place at least one drip line next to each plant off the block to provide extra water, as the cucumbers use a large amount of water once the leaves are fully expanded.

16.3.3 Pepper Seedling Culture

Similar to tomatoes, pepper seed germination may vary, so one must determine the amount of extra seed needed by use of the percentage germation given on the seed package. Add an extra 5–10%, as germination and vigor are not uniform. Many growers use small, round plug trays (Grodan Kiem plugs) to sow pepper seeds into granular rockwool. This allows them to select the most uniform, vigorous seedlings for transplanting to rockwool blocks. Rockwool cubes may also be used for initial sowing. At about 14–18 d, the peppers in the rockwool cubes can be spaced to double the area by cutting the cubes in strips and making two flats from every one. At the same time, lay the cubes and plants on their sides so that the stems will bend up, as that will make it easier to transplant them on their side into the rockwool blocks (Figure 16.7). Peppers are now also grafted similar to tomatoes; if that is done, do not place them on their sides as was discussed earlier for tomatoes.

FIGURE 16.6 Cucumber seedlings 27 d from sowing; 7 d after transplanting. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

FIGURE 16.7 Peppers double spaced and placed on their sides.

FIGURE 16.8 Peppers transplanted to blocks at 25 d. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

The B.C. Ministry of Agriculture recommends soaking pepper seeds with a 10% solution of trisodium phosphate (TSP) for 1 h before sowing to reduce virus infection. However, they warn of possible germination reduction because of the treatments. They also suggest using a 10% skim milk powder solution when handling the seedlings. The milk protein coats the virus making it noninfectious.

Soak the plugs or cubes with raw water of EC 0.5 mmho and *p*H 5.8. The seeds may be covered with coarse vermiculite or a polyethylene tent to obtain uniform temperature and humidity diuring germination. This applies especially to more northern regions having poor sunlight conditions during the winter months. After the seedlings emerge, use a dilute nutrient solution.

Germinate seed between 77°F and 79°F (25–26°C) and relative humidity (RH) from 75–80%. Maintain these temperatures during the day and night. As soon as the seedlings emerge, remove the tent, lower the air temperature to 72–74°F (22–23°C). Provide supplementary lighting as for tomato seedlings. About 4 d after emergence, permit the RH to decrease to 65–70%.

After 17–18 d from sowing seed, the seedlings are ready to transplant to 4-in. (10-cm) rockwool blocks when the first true leaves appear (Figure 16.8). Presoak blocks with a nutrient solution having an EC of 2.0–2.2 mmho and *p*H of 5.2. Slowly reduce air temperatures to 73°F (23°C) day and night. Space blocks at six per tray to allow enough room for them to grow for 3–4 wk (Figure 16.9).

Plants need to be supported by bamboo stakes if they are allowed to grow longer than 3–4 wk before transplanting to the production area (Figures 6.75 and 6.76). In northern areas, the peppers may be kept in the rockwool blocks up to 6–9 wk depending on the season. During this late stage of growth in the blocks (4 wk or more after transplanting into the blocks), raise the EC to 3.0–3.2 mmho. Enrich with carbon dioxide at 800 ppm. Similar to tomatoes, during transplanting the peppers maybe laid down or inverted to shorten their stems and produce more roots provided they are not grafted.

These recommendations are for more northerly regions of the United States, where peppers are seeded about mid-October for first fruit to set in early January.

FIGURE 16.9 Peppers 38 d old ready to transplant to pots or slabs. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

16.3.4 Eggplant Seedling Culture

Procedures for sowing and temperature, CO_2, and light requirements are very similar to tomatoes. Transplant the eggplants seedlings to rockwool blocks at about 17–18 d similar to peppers. Do not bend them down as may be done for non-grafted tomatoes and peppers. Follow the same procedures for presoaking of the cubes and blocks, EC, and *p*H as for tomatoes. After transplanting to the rockwool blocks, space them six to a tray as for the peppers. Within 2 wk they can be transplanted to the slabs or pots in the production area. By 8 wk from sowing and about 4 wk after transplanting to the pots they have to be trained to two stems and are setting fruit (Figure 16.10). Training of the plants is discussed in Section 16.13.

16.3.5 Lettuce Seedling Culture

For both raft culture and NFT, the best method of sowing seeds is in 1-in. rockwool cubes. Presoak the cubes with raw water similar to that of tomatoes and peppers. Use pelletized seed for automatic seeders. Generally, more uniform germination results from pelletized seed than with raw seed as the clay coating material retains moisture around the seed during the germination process. Always sow extra seed according to the percentage germination. Keep lettuce seed stored in the refrigerator to maintain its viablility. Do not store the seed for more than several months, as it soon loses its viability within 6 mo.

Once the cotyledons are fully expanded and the first true leaves begin to emerge, use a nutrient solution of EC 1.5 and *p*H 5.4–5.8. Optimum germination temperatures range from 59°F to 68°F (15–20°C). Temperatures in excess of 73°F (23°C) may induce dormancy. This may be overcome by placing the seeds on moist paper towels in a refrigerator at 36–41°F (2–5°C) for 48 h before seeding. In Anguilla the seeds were stored in a refrigerator at similar temperatures with no dormancy problems. If dormancy is a problem, keep the seeded trays at 61°F (16°C) until seedlings emerge. Maintain RH at 60–80% and carbon dioxide at 1,000 ppm during the day. Use supplementary lighting with a day length of 24 h at seedling emergence during winter months of cloudy weather in the northerly areas.

FIGURE 16.10 Eggplants 8 wk from sowing growing in bato buckets of perlite. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

Transplant to the production area of the greenhouse when three to four true leaves form at an age between 2 and 3 wk (Figure 16.11).

16.3.6 Herb Seedling Culture

Sow herbs in cubes or multicelled trays depending on the hydroponic growing system. Some herbs such as mint and rosemary are very slow in germinating, taking as long as 6–8 wk before they are ready to be transplanted. For such slow growing herbs, it may be better to use shoot cuttings to propagate them vegetatively. Cuttings taken from an existing crop will root within several weeks under a mist system with bottom heat. Sow small-seeded herbs such as mint, thyme, oregano, and so on in clumps of 6–10 seeds per cube or cell. Sow three to four seeds of basil and later thin to two per cube after 4 wk by cutting the extras off with a scissors. However, if growing "live herbs" do not thin and seed up to five to six per cube.

Favorable temperatures range from 65–75°F (18–24°C). A *p*H of 5.8–6.2 and an EC of 1.6–2.5 mmho are suitable. Conditions similar to those for lettuce are generally good for herbs. During periods of cloudy weather, it may be necessary to raise the EC to prevent succulent growth. Since herbs are not a large greenhouse crop, one must rely on experience in one's region to determine the more optimum environmental conditions.

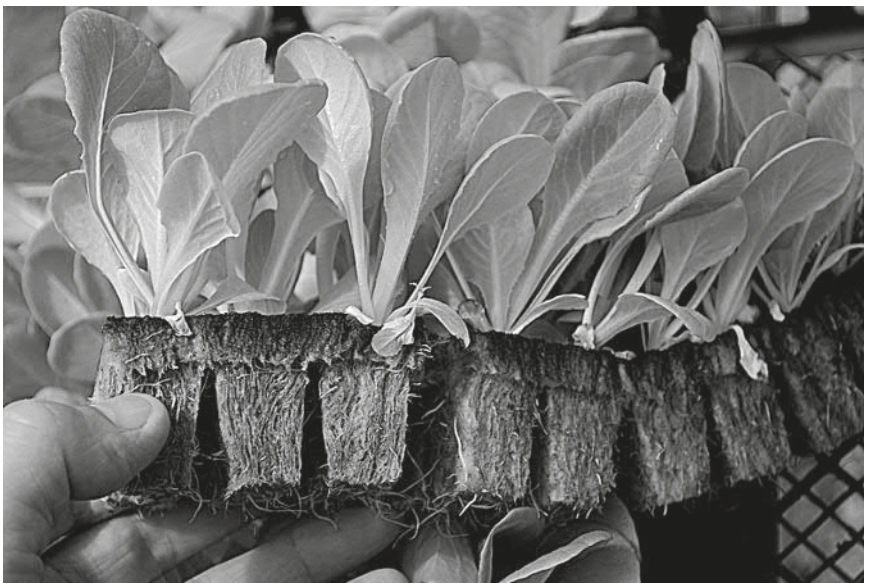

FIGURE 16.11 Bibb lettuce at 20 d in rockwool cubes ready to transplant. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

16.4 PLANT-GROWING TEMPERATURE

Usually better quality plants are grown when night temperature is 10°F (5.5°C) lower than day temperature. The best temperature range for warm-season crops is 60°F (16°C) at night and 75°F (24°C) during the day. Cool-season crops will do better at 50°F (10°C) night and 60°F (16°C) day temperatures. A 10°F (5.5°C) lower day temperature is best during periods of cloudy weather. These ranges are only guidelines. Specific optimum minimum and maximum temperatures depend on species and even varietal differences. In tomatoes, if the day-night temperature differential is too great, long upright clusters form, which will later kink and possibly break under fruit development.

If temperature is too low, plant growth will be slower and some purpling of leaves may occur, especially on tomatoes. If the temperature is too high, growth will be soft and "leggy," resulting in poor-quality plants.

The optimum temperature for the tomato plant varies with the stage of plant development (Table 16.1). Tomato plants grown under optimum temperature and light conditions develop large cotyledons and thick stems, with fewer leaves formed before the first flower cluster, greater number of flowers in the first and often the second clusters, and higher early and total yields.

16.5 LIGHT

During cloudy weather, tomato leaves become low in sugars. Leaves and stems become pale and thin, and the fruit clusters may be smaller or fail to set. Excess nitrogen during such a period can be harmful. Supplementary artificial lighting has generally been found to be economically impractical except in the raising of seedlings, as mentioned earlier.

During bright, sunny weather, sugar production in the leaves is high. The leaves are dark and thick, stems are dark green and sturdy, fruit sets well with large clusters and root systems are vigorous. Nitrogen can be supplied at a heavier rate during this period.

TABLE 16.1
Night and Day Temperatures from Seed Germination to Fruiting of Greenhouse Tomatoes, European Cucumbers, Peppers, Eggplants, and Lettuce

	Temperature, °C (°F)	
Growth Stage	**Night**	**Day**
Tomatoes		
Seed germination	24–26°C (75–79°F)	24–26°C (75–79°F)
After emergence, until 1 wk before transplanting	20–22°C (68–72°F)	20–22°C (68–72°F)
For 1 wk	18–19°C (64–66°F)	18–19°C (64–66°F)
After transplanting, until start of harvesting	16–18.5°C (61–65°F)	21–26°C (70–79°F)
During harvesting	17.5–18.5°C (63.5–65°F)	21–24°C (70–75°F)
European Cucumbers		
Seed germination	27–28°C (81–82°F)	27–28°C (81–82°F)
After germination (about 2 d)	24–25°C (75–77°F)	24–25°C (75–77°F)
First transplant to blocks	21–22°C (70–72°F)	23–24°C (73–75°F)
Several days before transplant to greenhouse	20°C (68°F)	22°C (72°F)
After transplant to slabs (use lower temperatures of these ranges as plants reach overhead wires)	16–20°C (62–68°F)	21–24°C (70–75°F)
Peppers		
Seed germination	25–26°C (77–79°F)	25–26°C (77–79°F)
After seed emergence	22–23°C (72–73°F)	22–23°C (72–73°F)
After transplanting	17.5–18°C (64–65°F)	23–23.5°C (73–74°F)
Growth and harvesting	19°C (66°F)	22°C (72°F)
Eggplants		
Seed germination	25–26°C (77–79°F)	25–26°C (77–79°F)
After seed emergence	23–24°C (73–75°F)	23–24°C (73–75°F)
After transplanting	20–21°C (68–70°F)	21–23°C (70–73°F)
Growth and harvesting	17–19°C (63–66°F)	20–22°C (68–72°F)

TABLE 16.1 (Continued)
Night and Day Temperatures from Seed Germination to Fruiting of Greenhouse Tomatoes, European Cucumbers, Peppers, Eggplants, and Lettuce

Growth Stage	Temperature, °C (°F) Night	Day
Lettuce		
Seed germination	15–20°C (59–68°F)	15–20°C (59–68°F)
Seed emergence through transplanting	15–18°C (59–64°F)	15–18°C (59–64°F)
Production to harvest	15–19°C (59–64°F)	19–25°C (66–77°F)

(To convert from temperatures in Fahrenheit to those in Celsius, use the following formula: (F-32) x 5/9 = C, where F = degrees in Fahrenheit; C = degrees in Celsius.)

When the weather is cloudy for more than 1 or 2 d, it may be necessary to do the following:

1. Reduce day and night temperatures in the greenhouse 3–4°F (2°C).
2. Use as little water as possible but do not let the plants wilt.
3. Adjust the nutrient-solution formulation to increase the EC.

These steps will help to keep plant growth balanced between leaf growth and fruit production. If they are not observed, the plants are likely to be very dark green and healthy, but are not likely to set many fruit.

During the seedling stage, plants should be transplanted to wider spacing in flats [at least 2 in. (5 cm) apart] or to individual containers at full cotyledon development or very early first-true-leaf stage (Figure 16.2) to reduce mutual shading. In flats, plants should be set out in about 3 wk to avoid spindly development. In individual small containers or growing blocks, plants can develop longer than 3 wk, provided they are spaced out as they grow to avoid crowding. Excellent plants can be grown in 3- or 4-in. (7.6- or 10-cm) pots or blocks, but they require more nursery space than do small containers. At this stage, generally six plants per flat is ideal spacing. Space them sufficiently to prevent leaf overlapping during growth. Good containerized plants have pencil-size stems and are about as wide, from leaf tip to leaf tip, as they are tall (Figure 16.4).

In northerly latitudes, during short, dull days of winter months, supplementary lighting should be used to provide additional intensity of light and to extend the day length. Seedlings at this stage should be provided with supplementary lighting to obtain a DLI of of 13–16 mol/m^2/d as discussed earlier. At present, the most efficient lights for greenhouses are HID plant grow lights. They include MH and high-pressure sodium (HPS) lamps. MH lamps produce light in the blue spectrum and HPS bulbs emit an orange-red glow. MH lights are best for leafy growth to keep plants compact and are used mainly for controlled environments with little natural sunlight, whereas HPS lights increase flowering and are best for supplementary lighting with natural sunlight, as is the case in greenhouses.

HID lights come in 100, 250, 400, 600, 1,000, and 1,500 W. One unit will give adequate lighting for an area of 2 ft x 2 ft, 3 ft x 3 ft, 4 ft x 4 ft, 5 ft x 5 ft, 6 ft x 6 ft, and 8 ft x 8 ft, respectively. If the lights are used as supplementary to natural sunlight, the coverage area can be increased by about 50%.

The height to hang them above the crop is dependent on the wattage. Low-wattage systems (100 and 250 W) should be located at about 2–3 ft (61–91 cm), medium-output systems at 4 ft (1.23 m), and high-wattage systems (1000 W and above) at about 4–6 ft (1.2–1.8 m).

There are switchable ballasts that allow growers to use either MH or HPS lamps. This enables the grower to change from the MH in the early vegetative stage of growing to HPS as the plants are to be steered toward a generative (flowering-fruit production) stage. An alternative is to also use a small percentage of MH units mixed with the HPS ones if growing under natural sunlight conditions of a greenhouse.

The section of the visible light that is useful for plant photosynthesis ranges from 400 nm of wavelength through 720 nm. The 400–520 nm range includes violet, blue, and green light; 520–610 nm includes green, yellow, and orange bands; and 610–720 nm includes the red band, where there is a large amount of absorption by the chlorophyll pigment during photosynthesis and promotion of flowering.

For more information about lighting and the use of LED lights, refer to Chapter 12.

If supplementary lighting is to be used in the growing area, contact a light manufacturer or their distributors to have them lay out the design and choose the best units to use for specific crops. Simply provide them with a plan of the greenhouse and the areas within it with the specific crops. One such lighting manufacturer is P.L. Lighting Systems (www.pllight.com).

16.6 RELATIVE HUMIDITY (RH) AND VAPOR PRESSURE DEFICIT (VPD)

Humidity is the quantity of water present in the air as vapor. RH is the amount of humidity present expressed as a percentage of the maximum possible at a given temperature. When air is completely saturated, it has a RH of 100%. Heating of the air reduces the RH and cooling increases it. Increasing the air temperature by 10°C (18°F) almost doubles the water holding capacity of the air and therefore halves the RH. With a full crop in the greenhouse, plants will cool the air temperature by releasing water into the atmosphere by transpiration.

The relationship between RH and temperature affects the crop in a greenhouse. For example, if the greenhouse day temperature is 25°C (77°F) with 50% RH and at night the temperature falls to 15°C (59 °F) the RH will rise to 90%. The RH within the crop will be even higher. Such high RH favors diseases. Ventilation is critical to lower the RH. Horizontal air-flow fans (HAF) mix up the air and will reduce the RH within the crop. Raising the temperature and ventilating with overhead vents or exhaust fans will assist in lowering the RH. Outside air can be drawn into the greenhouse by convection tubes and heated before entering the crop. This will reduce the RH. Large convection tubes under plateau gutters with the plants or overhead convection systems can bring in cold outside air that is heated before it reaches the crop.

Broad (2008) explained clearly the relationship between relative humidity and VPD. At present greenhouse operators measure and control moisture within the atmosphere by using the term vapor pressure deficit (VPD). Refer to Chapter 12 for further information on RH and VPD.

If the VPD is too low, the temperature may be too low and/or the RH is high, causing the crop to be vegetative, soft, and with weak growth. If the VPD is too high, the crop is stressed and may become hard, stunted, and very generative. A good balance between vegetative and generative phases of plants is essential to productivity, as is discussed in Section 16.10. VPD, temperature, nutrient formulations, and irrigation cycles are important in manipulating this balance between vegetative and generative phases.

16.7 CARBON DIOXIDE ENRICHMENT

In northern regions, carbon dioxide enrichment in greenhouses has improved productivity substantially. Commercial greenhouse operators claim a 20–30% increase in tomato yields; better fruit set

in early clusters, especially when low light levels would normally reduce fruit setting; and larger fruits. In Ohio, cucumber yields have increased as much as 40%. Lettuce yields have increased 20–30% per crop, and faster growth rates have allowed production of an extra crop each year.

Carbon dioxide enrichment and supplementary artificial lighting is economically feasible to produce vegetable seedlings and bedding plants. These practices produce sturdier plants in much less time than conventional systems.

For maximum profits, there is an optimum CO_2 concentration that should be present inside the greenhouse, which depends on the stage of growth and species of crop, as well as the location, time of year, and type of greenhouse. Generally, levels at two to five times the normal atmospheric levels (1,000–1,500 ppm CO_2) may be taken as the optimum levels.

On cool days, when greenhouses are being heated and air vents are closed, plants will deplete the CO_2 in the greenhouse atmosphere. In 1 h, plants in a closed greenhouse may lower the CO_2 concentration enough to significantly reduce growth rates. Air venting to maintain CO_2 concentration at outside levels would increase heating costs substantially. In these circumstances, special heaters using propane, natural gas, or fuel oil can supply CO_2 while simultaneously raising temperatures.

Carbon dioxide enrichment is of special significance in hydroponic culture since one of the sources of the gas, decaying organic matter in the soil, is not present. Carbon dioxide enrichment may be expected to increase fertilizer and water requirements, since plants will be growing more vigorously. Young tomato plants are especially responsive to CO_2 enrichment. Wittwer and Honma (1969) claimed that growth rates can be increased by 50% and early flowering and fruiting accelerated by a week or 10 d. Effects are carried into the fruiting period.

Not only is top growth and flower formation accelerated but root growth is also promoted even more. In general, the optimal carbon dioxide levels during the day for tomatoes, cucumbers, peppers, and lettuce are 700–1,000 ppm, 800–1,200 ppm, 800–1,000 ppm and 1,000–1,200 ppm respectively.

16.8 TRANSPLANTING

Good-quality transplants are essential to a good greenhouse crop. They must be set into the beds, pots, or on slabs properly and cared for afterward to avoid any check in growth. For the least amount of transplanting shock, plants should be the right age and moderately hardened. Tomato or pepper plants should not have any fruit set.

Containerized plants undergo less transplant shock than bare-root plants because there is little or no disturbance to the root system. The transplanting shock of bare-root plants can be minimized, however, with proper planting and care.

When transplanting tomatoes to gravel medium, the crown area of the stem may be set below the bed surface up to 1–2 in. (2.5–5 cm) to provide better initial support for the plant. This also allows new roots to develop on the buried stem section. With leggy plants, 4–5 in. (10–12.5 cm) of stem may be buried on an angle. The above-ground portion will grow vertically from where it enters the medium. With rockwool culture, it is common practice to bend the stem from a right angle to a complete inversion when placing seedlings from the propagation cubes to the blocks, but do not do this with grafted plants. With perlite culture, if the seedlings from propagation cubes are planted directly into perlite bato buckets without the use of rockwool blocks, they can be turned at a right angle or inverted into the perlite. This same practice may be used for peppers, but not for cucumbers or lettuce. These vegetables should be transplanted with their crowns positioned at the medium surface, not below it, or severe disease infection can occur in the crown.

Irrigate the plants as soon as possible after they are set to avoid or minimize wilting. In gravel culture, the beds can be flooded while transplanting to maintain a high level of water in the coarse medium. Before planting, keep the containers or flats of plants moist. Properly set container plants will not wilt following transplanting, if their root balls are moist when planted and irrigation follows

soon afterward. Bare-root plants may wilt after planting, even though irrigated immediately, but they will recover overnight.

Coco coir and perlite substrates are becoming more popular as discussed in Chapters 11 and 13 because they do not have the disposal problem of rockwool.

16.9 SPACING

Most publications on greenhouse tomato production suggest space allowances of 3.5–4 ft^2 (0.3–0.37 m^2) per plant (12,000–10,000 plants per acre). Plants may be arranged in double or single rows. The most recent method is to use a V-cordon arrangement of training tomatoes and peppers where every other plant is supported to the opposite overhead wire similar to that shown in Figure 16.27 for cucumbers. Plants are arranged in single rows, having double the plants per rockwool or coco coir slab (usually four to five plants per slab). Refer to Chapter 10 for more details. The same plant density is used at 3.5–4.0 ft^2 per plant.

Peppers are spaced similarly to tomatoes, with planting densities of 8,000–10,000 plants per acre (20,000–25,000 plants per hectare). This is equivalent to 3.3–3.5 plants per square meter of greenhouse area. Peppers are trained to two stems per plant, increasing the density to 6.5–7 stems per square meter. Eggplants are arranged at the same density and spacing as peppers, with two stems per plant.

If double rows are used, place three plants per slab, whereas in a single row use five plants per slab. Most growers use single rows, with the plants trained in a V-cordon configuration to the overhead support wires. For double rows, space each row 40 cm (16 in.) apart and 1.46 m (57 in.) between the drainage/irrigation lines. Slabs are spaced 23 cm (9 in.) apart within each row using 100 cm (39 in.) long slabs. In a single-row configuration, rows are 1.8 m (71 in.) apart, and the slabs are placed together end to end within the row.

European cucumbers require a minimum row width of 5 ft (1.5 m). For the spring/summer crop, the plants require 7–9 ft^2 (0.65 to 0.84 m^2) for each plant, and for the fall crop 9–10 ft^2 (0.84–0.93 m^2). This is a population of 5,000 plants per acre or 12,500 plants per hectare. Plants can be placed in single rows 14–16 in. (35.5–41 cm) apart within the row. Tie plants alternately to overhead wires spaced 2.5–3 ft (0.76–0.9 m) apart in the V-cordon method (Figure 16.27), permitting more uniform light on the plants.

16.10 VEGETATIVE VS. GENERATIVE GROWTH

Plants have two phases of growth, vegetative when leaves and stems are growing rapidly, and generative, when they are blooming and forming fruit. In crop production we must maintain a balance between vegetative and generative phases to maximize yields. Initially, when plants are young we emphasize the vegetative phase to get them established with relatively large leaves and stems. This phase is important in establishing sufficient photosynthetic area for the plant to produce sugars that are later used in production of fruits. Once the plant has sufficient leaf area to support fruit formation, we wish to shift it into a more generative phase. In this phase, the sugars are shifted into flower and subsequent fruit formation. In this way, the plant is capable of producing larger and more fruit. For example, as discussed later, in European cucumbers we remove the first eight flowers to keep the plant vegetative, forming large leaves that will later provide photosynthates in forming fruits. As mentioned earlier, with tomato seedlings we want the stems to be pencil thick and the leaves large so that the transplant's area is as wide as high. This initial vegetative growth prepares the plant for later fruit development.

As the plants begin to form fruit, it should be possible to shift their growth to more generative or more vegetative, depending on their growth rate. This can be done by changing certain environmental and nutritional factors. This manipulation of the plant environment to shift it to more

vegetative or generative growth is termed *plant steering*. Try to change only one or two factors at a time and look for the desired results. If these changes do not give the needed response, change others. Generally, tomatoes should be steered toward generative growth early in their development. Peppers when young must establish strong vegetative plants before fruit production. This is similar to eggplants. Cucumbers also must establish strong vegetative growth before fruit production. Steering of the plants is accomplished by manipulation of temperatures, irrigation cycles, EC, and pruning. The balance can be influenced by day and night temperatures. The grower must become familiar with the vegetative and generative characteristics and alter the environment and feeding program to acquire the desired result.

With peppers, high light and temperatures direct plants to remain generative. Being too generative will result in small fruit. Maintain six fruits per stem (10–12 fruit per plant). Excessive fruit may stop or slow plant growth, resulting in decreased fruit weight and size. Flowers should not be higher than about 10 cm (4 in.) from the growing tip of the plant. To make the plants more vegetative, raise the night temperatures and reduce the day temperatures, keeping the 24-h average at 20–22°C (68–72°F). Under lower light intensities of fall months, the 24-h temperature range can be lowered to 20°C (68°F), with night temperatures at 17–18°C (63–64°F) and day temperatures at 20–21°C (68–70°F). Maintain carbon dioxide levels between 800 and 1,000 ppm. Under high light conditions, shading of 25–30% will reduce sunscald and cracking of the fruit.

During fruit production of cucumbers, night temperatures should be maintained at 18–19°C (64.5–66°F) and day temperatures at 21–23°C (70–73°F). Therefore, the 24-h temperature will be about 20.5–21°C (69–70°F).

16.11 IRRIGATION (FERTIGATION)

Once the plants have been transplanted, the feeding-irrigation system cycles must be set. The time between irrigation cycles depends on a number of factors, as discussed earlier, including the type of growing medium used. Regardless of the hydroponic growing system (rockwool, sawdust, perlite, peat-lite, coco coir), a drip irrigation system with a fertilizer injector is used to provide the plants with water and nutrients. Most hydroponic greenhouses use fertilizer injectors with stock solutions. In the past, two-part stock solutions A and B in separate storage tanks use concentrated nutrient formulations from 100 to 200 times the normal strength. In addition, a stock solution of acid or base in the third tank adjusts the *p*H of the final solution. At present, more growers are setting up the stock solutions separately for each fertilizer salt for the macroelements and a separate one for minor elements. The reason for this is versatility in adjustment of the nutrient formulation. These adjustments

TABLE 16.2
Tomato Plant Characteristics of Generative versus Vegetative Phases

Characteristic	Too Generative	Too Vegetative
Leaves	Short, dark, and firm	Long, open or springlike curled, light-green, and soft
Truses	Stems are thick, sturdy,	Thin, long, bent upwards short, and curved
Flowers	Dark yellow, close to top of the plant, open fast and uniformly within the truss	Light yellow, form far under the top of plant, open poorly, sepals stick together
Fruits	Many fruits (4–6) form quickly with good shape	Few fruits develop slowly, small, with poor shape, may be deformed

TABLE 16.3
Parameters to Shift Tomato Plants More Vegetative or More Generative

Parameter	More Vegetative	More Generative
Irrigation cycle length and frequency	Shorter and more frequent	Longer and less frequent
Start irrigation	Earlier	Later
End irrigation	Later	Earlier
Leachate	More leaching, EC lowers	Less leaching, EC rises (cloudy)
Moisture deficit	Lower	Raise
Temperature difference day to night (0–5°C) (0–9°F)	Smaller	Larger
Carbon dioxide (350–1,000 ppm)	Less	More
EC-irrigation (2.5–4.0 mmho)	Lower	Higher
Truss Pruning	More (4 fruits)	Less (5–6 fruits)

Tables 16.2 and 16.3 are based on characteristics of tomatoes, but the general principles apply to other fruit-bearing crops.

are made during changes in sunlight conditions and enables flexibility in steering the plants. The injector dilutes these concentrates proportionally with water in a blending or mixing tank or in large main lines as the solution is pumped through the drip irrigation system.

As described earlier in Chapter 3, new systems utilize computer feedback systems that monitor and adjust the return solution from the crop. Now such recirculation systems are part of the sustainable yields program to conserve water and efficiently utilize the use of fertilizer salts.

Frequency and duration of irrigation cycles depends largely on the substrate water retention characteristics. Rockwool needs less irrigation than perlite. See Chapter 10 on rockwool culture for specific details. Coco coir irrigation cycles are more similar to a peat-lite substrate, as was described in Chapter 11. More frequent irrigation is needed after transplanting until the plants become established in the substrate. After that, 5–10 irrigation cycles per day may be adequate, depending on environmental conditions and plant stage of growth. Perlite generally needs more frequent irrigation cycles than rockwool as it has less water retention.

16.12 PLANT SUPPORT

Vine crops such as tomatoes, peppers, eggplants, and cucumbers must be trained vertically to maximize production. Training must begin as soon as the plants are transplanted into their final growing system. Support the plants with plastic twine attached to overhead cables. Any vine crop, such as tomatoes, that must be lowered during their crop cycle requires plant hooks, such as "Tomahooks." These hooks have additional string wrapped on them to permit the lowering of the vines as they grow upward (Figure 16.12). The hooks can be purchased already wound with extra string. Additional string needed is at least 20 ft (6 m). Attach the strings to cables located directly above the plant rows at a height of the greenhouse gutters or a maximum of about 5–6 m (16–20 ft) for the new glass Venlo greenhouses having gutters of 7 m (23 ft) or higher as can be seen in Figure 12.15.

The support string is attached to the bottom of the plant by the use of a plant clip below a healthy leaf. This is done during transplanting to begin training the plants vertically. As the plants grow, the string may be wrapped around the stem, always in the same direction (generally clockwise), and occasionally a plant clip may be placed under a leaf petiole to give additional support (Figure 16.13).

FIGURE 16.12 Plant "Tomahooks" attached to overhead support cable. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

FIGURE 16.13 Place stem clamps under a strong leaf.

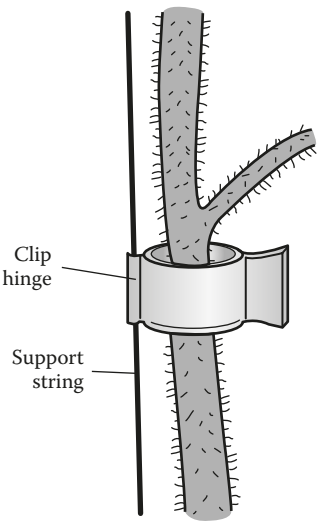

FIGURE 16.14 Correct positioning of plant clips and fastening to support string. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

The string is always wound around the stem of the plant in the same direction to avoid other workers accidentally unwinding the strings. Most growers use this method, but one can also just use plant clips about every foot in plant length as it grows without winding the string around the stem.

Peppers and eggplants should not need to be lowered as long as the support cables are at least 14–15 ft (4.5 m) in height. This is possible in most greenhouses that have gutter height of 5 m (16 ft) or higher. Lowering peppers and eggplants in lower greenhouses is possible, but must be done with care, as the vines are brittle and break easily. When doing so only a few leaves should be removed, as the plants get very stressed. Eggplants are even more sensitive to lowering and tend to lose leaves due to senescence afterward.

All vine plants must be clamped to the string before they fall over. Secure the first clamp under a large leaf pulling the twine taut, but not so tight that when released it will pull the leaves up.

Clamping should be positioned as shown in Figures 16.13 and 16.14. Clamps should be placed directly under the leaf petioles, not above them, as such a position gives no support. Clamps should not be placed directly under flower clusters, as the weight of maturing fruit later (in the case of tomatoes) may break off the fruit cluster or fruit may be punctured by the clamps. With peppers it is important that the clamps are not set directly below the small fruit, as when the fruit expands it will grow into the clamp, deforming the fruit as shown in Figure 16.15. Secure plant clips about every foot (30 cm) along the plant stem to give adequate support. The back hinge of the clamp must pinch the string as shown in Figure 16.14.

16.13 SUCKERING AND TRAINING (TOMATOES, CUCUMBERS, PEPPERS, AND EGGPLANTS)

Suckers are the small side shoots that grow between the main stem and the leaf petioles. They must be removed before they grow too large, as they drain the nutrients of the plant, which could otherwise go into fruit development. With tomatoes, they should be removed when they are about 1–2 in. (2.5–5 cm) long (Figures 16.16 and 16.17). At this stage, they can be easily snapped off by hand without creating a large scar of the axillary region (area between stem and petiole). With eggplants and peppers, remove the side shoots at the first or second node (Figures 16.18 and 16.19) depending on the ability of the side shoot to support the fruit.

FIGURE 16.15 Pepper fruit deformed by plant clip.

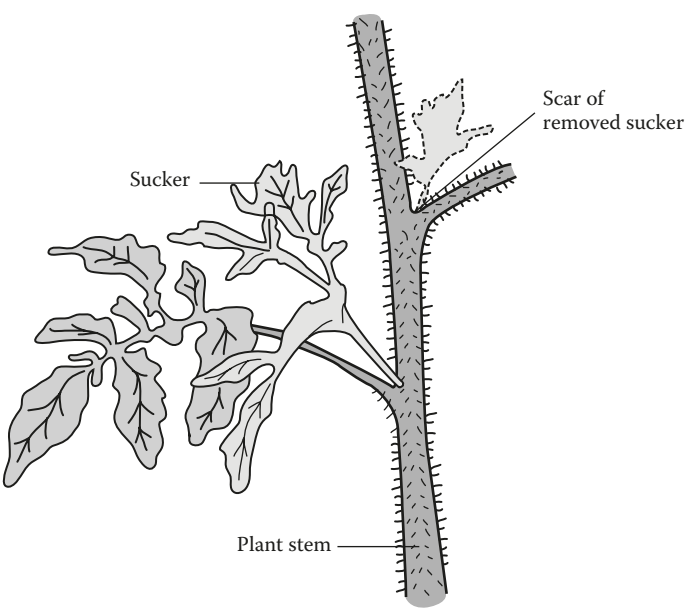

FIGURE 16.16 Removal of tomato suckers at early stage. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 16.17 Tomato sucker ready to be removed. Note: The flower truss above with a side shoot growing from it that needs to be removed also.

With tomatoes, remove suckers by hand, which presents less hazard of spreading diseases than using a knife or pruning shears. Rubber or disposable latex gloves should be worn to protect the hands from the acidic sap of the plants. Larger suckers, which may develop because of late suckering, will have to be removed with pruning shears or a knife.

Often, with tomatoes, terminated plants (those no longer having a growing point) will be encountered. Select a vigorous sucker near the growing point and allow it to continue growing, but remove other less vigorous suckers. Some plants may fork or split. Again, select the most vigorous branch and prune off the other growing point (plant apex).

Cucumber side shoots can be removed when they are smaller, more or less the same size as with tomatoes (Figure 16.20). This is a daily task when the plants are growing their principal stem before reaching the overhead supporting cable. Also, all tendrils as shown in Figure 16.21 must be broken off for the entire life of the plant as the tendrils tangle up the leaves and fruit, causing distortion and difficulty in the fruit hanging up, which will cause curved fruit.

As tomato plants mature and the fruits have been harvested from the lower trusses, the older leaves on the bottom of the plant will begin to senesce (yellow) and die. These leaves should be removed to allow better air ventilation and thus lower the RH around the base of the plants. Start taking them off from the time the second truss (fruit cluster) has been completely harvested. After that, continue removing leaves which turn yellow, up to the truss, then bearing mature fruit. In the past, it was recommended to simply snap off the leaves with your fingers, but now more growers are

FIGURE 16.18 Side shoot of eggplant.

using a sharp knife to get a clean surface to minimize scars. Remove all the dead leaves from the greenhouse and dispose of them by burying them in a pit or haul them to a landfill. This leaf pruning can be repeated many times as the plants mature, usually once a week when the plants are lowered. Generally, no more than three to four leaves should be removed at any time and not more frequently than once per week. The exception is when the plants are to be steered more toward being generative during their early stage once they reach about 3–4 ft (1 m) in height. Removing lower leaves will stress them and shift them to being generative.

As the tomato plants reach the support cables above, unwind the support string and lower the plants 12–16 in. (0.3–0.4 m) each time. Since the lower leaves and fruit have been removed, the stems can be bent to rest on plant stem support wires as described in Chapter 10. Lower the plants slowly to avoid breaking the stems. At all times, about 6–7 ft (1.8–2 m) of foliage and fruit clusters should remain on the upper part of the plant (Figure 16.22).

Flower trusses on beefsteak-type tomatoes may be pruned to select the most uniform four- to five-set fruit on a truss (Figure 16.23). Any misshapen flowers, double set fruit, and often the furthest flower out on the truss are removed. This gives uniform fruit development, shape, size, and color of tomatoes. Blossoms and small fruit should be removed as soon as two or three fruits set to pea size.

With many of the beefsteak varieties, which set fruit heavily, as the fruit develops on the truss, the weight of the fruit causes the truss to buckle or break, resulting in lost production. Truss-support clips and hooks have been developed to prevent such breakage. They are inexpensive plastic flexible

FIGURE 16.19 Remove side shoots on peppers at either the first or second node. Note: The main shoot has the plant clips.

supports that easily snap onto the truss stem early after fruit set, whereas the hook is attached to the truss and support string as shown in Figures 16.24 and 16.25.

Long English (European) cucumbers are grown in greenhouses since they can be trained vertically and cannot withstand the outside temperature fluctuations.

European cucumbers should be trained under two systems: The renewal umbrella system (Figure 16.26), and the V-cordon system (Figure 16.27). A V-cordon system trains the plants to make best use of available light within the greenhouse. Over each row of plants two support wires are placed 7–10 ft (about 2–3 m) above the floor, or close to gutter height when using carts to work on the plants. Since most greenhouses now have high gutters of 6–7 m (20–23 ft), the plants can be trained to 5–6 m (16–20 ft). The cables are spaced 2.5–3 ft (0.75–1 m) apart. The support strings are then tied alternately to the two overhead wires so that the plants are inclined away from the row on each side (Figure 16.27). Suckering and trimming of cucumbers is necessary to obtain a balance between the vegetative vigor and fruit load of each plant. Suckers, and also all blossoms and fruit, should be removed up to the sixth or seventh true leaf. All tendrils must be removed daily (Figure 16.21).

If too many fruits are allowed to form at any one time, and too early, a large portion will abort because the plant may not have sufficient food reserves to develop them. If a heavy load of fruit sets,

FIGURE 16.20 Sucker of European cucumber ready to be removed. Note: The small fruit next to the sucker.

often malformed or poorly colored fruits develop, which are unmarketable. Remove them at an early stage as shown in Figure 16.20. Multiple fruits in one axil should be thinned to one.

The renewal umbrella system of training plants is achieved by the following steps:

1. The main stem should be stopped at one to two leaves above the support cable. Cut off the growing point at that level. It is better to leave three side shoots, two below the cable and one above it, and then thin out the third one once the side shoots begin to elongate. The reason for this is to have an extra one available in case one does not form properly. Fasten a plant clip under the last leaf below the wire to prevent the top from sliding back down.
2. Do not allow fruit to develop on the main stem up to six to seven leaves to promote vegetative growth that results in large leaves that are capable of manufacturing adequate food reserves for the fruit above.
3. Remove all laterals (side shoots) in the leaf axils on the main stem, except the two to three at the top.
4. Train the top two laterals over the cable to hang down on either side of the main stem. Allow these to grow to two-thirds of the way down the main stem. Training the main stem and laterals over the support cable can damage the plant if care is not taken. To overcome this problem, use a plant clip after the first axil of the lateral to attach it to the support cable as shown in Figure 16.28.

FIGURE 16.21 Tendrils of cucumbers must be taken off daily.

FIGURE 16.22 Removal of lower leaves and setting of bare stems on support bars. (From Houweling's Group, Camarillo, CA. With permission.)

FIGURE 16.23 Prune fruit from trusses while fruit is small.

5. Remove all secondary laterals, except two at the top.
6. While the fruit on the first lateral are maturing, allow the second laterals to grow out and downward.
7. When the fruits on the first lateral have been harvested, remove them completely, allowing the second laterals to develop.
8. Repeating steps 5, 6, and 7 will maintain fruit production.

Some growers carry a cucumber crop for 10 mo using this renewal umbrella system and obtain over 100 cucumbers per plant. However, it is more productive to use two to three crops annually to get more vigorous plants that yield higher. In the warm climates of the semitropics and tropics it is better to change the crops every 3 mo. In Florida, that was the most productive system of cropping. In Anguilla, the crops are changed every 10–11 wk as the plants grow from seed to first production within 5 wk.

There is a modified umbrella system that some growers use to potentially produce more fruit per plant (DeRuiter, 2019) (Figure 16.29). It eliminates the lag in fruit production as normally occurs in the renewable umbrella system of training once the main stem fruit have been harvested. In the modified umbrella training the main stem is not cut when it reaches the overhead support wire, but is allowed to continue to grow over a second and possibly a third, overhead support wire. One lateral is trained over the first support wire in one direction and four other laterals that develop on the main stem are trained over the other support wires in the opposite direction.

The potential advantage of this modified umbrella system is more fruit production per plant with larger fruit. In the high-wire system fruit production up to 200 fruit per square meter may be achieved, but there is an increase in labor requirements associated with the high-wire system. With the modified umbrella system production is somewhat lower, but there is significantly lower labor in pruning and harvesting.

At present, the most common method is the “high-wire” system in which cucumbers are planted in raised trays, as described in Chapters 10 and 11, using coco coir or rockwool slabs (Figure 16.30). The high-wire training system is similar to the “lowering and leaning” system of training tomatoes. High-wire training of cucumbers requires a minimum gutter height of 14.5 ft (4.4–4.5 m). The

FIGURE 16.24 Truss support hook attached to truss and support string.

objective of this training is to produce more fruit per unit area compared to the renewal umbrella training. In the renewal umbrella system from 150 to 160 fruits of cucumbers per square meter may be produced compared to 180 to 220 fruits per square meter with the high-wire training system. However, as mentioned above, the high-wire training system comes with a significant increase in labor, which must be offset by the marginal increase in production. More labor is needed in clipping, lowering and leaning, pruning, and removing leaves.

The high-wire training method and advantages:

1. Regular lowering and leaning of the plants using Tomahooks and plant clips to slide the plants along the overhead support wire. Care must be taken not to break the vines. The lower parts of the plants need support above the growing slabs similar to tomatoes.
2. Fruit production is more uniform in not having large numbers of fruits maturing at once.
3. The lag between the termination of stem fruit and the first production of the overhead laterals in the renewal umbrella system is avoided.
4. Less density of leaves with an open canopy remains more constant than with the renewal umbrella system when the overhead laterals form a dense canopy. There is less curved fruit that develops in the high-wire system because the fruit hangs free of the stem with no obstructions from many leaves and vines as is the case in the renewal umbrella training.
5. Pest and disease management is easier and more effective in the open canopy of the high-wire system.

FIGURE 16.25 Truss clip on fruit cluster to prevent kinking.

Hao et al. (2010) did research on a "twin-head" V-cordon high-wire training alternative to reduce start-up costs. The conventional high-wire system for cucumbers is to train each plant as a single stem. The high-wire system requires higher density of planting than the traditional renewal umbrella system. Hao et al. (2009) stated that for a single stem plant with the high-wire training 2.2–4 plants/m^2 density is needed compared to 1.4–1.8 plants/m^2 with the umbrella system. The research of this paper was to determine if a technique for raising the plants with two stems (twin-head) would give similar production as single-stemmed plants. In this technique the transplants were made to twin-head by topping the seedlings after the emergence of the fourth true leaf. The two strong lateral shoots were allowed to be trained into a "V" high-wire system after planting (Figure 16.31). The results of the trials showed that the twin-head plants trained in this way produced equally as the single-stemmed plants. The study concluded, "The twin-head "V" high-wire system is a more cost-effective high-wire system for year-round greenhouse cucumber production."

Beit-Alpha (BA) (Japanese cucumbers or Persian pickles) are trained somewhat differently. BA cucumbers are also seedless, burpless, similar to the European cucumbers, but are much smaller. They are usually from 5 to 7 in. (12.5–18 cm) in length 1.25 in. (3.5 cm) in diameter (Figure 16.32). They are sometimes termed *mini cucumbers*. It is important that they are resistant to powdery mildew (PM) (Shaw and Cantliffe, 2003). In our trials of different varieties we found that under the tropical conditions of Anguilla, the most productive and most resistant to PM was "Manar," a variety of DeRuiter Seeds (Resh, 2009).

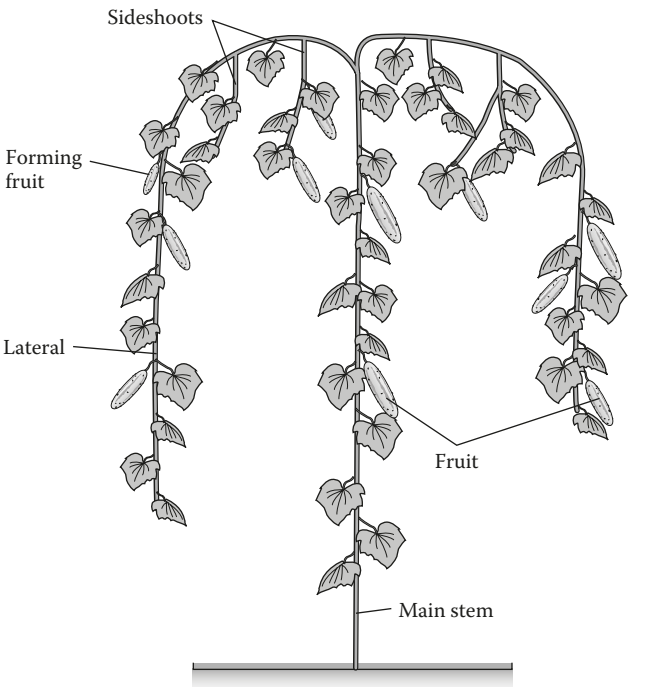

FIGURE 16.26 Renewal umbrella system of training European cucumbers. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

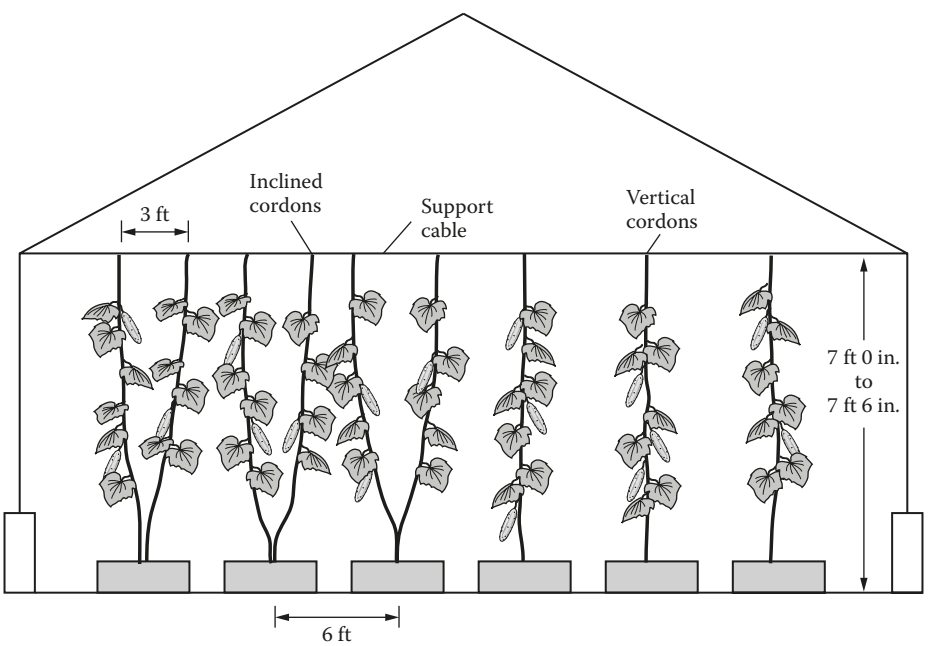

FIGURE 16.27 V-cordon system of training European cucumbers. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 16.28 Attaching plant clips on lateral shoots to support cable and at top of the main stem. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

Spacing of BA cucumbers is about half of that of the European types, usually about two to three plants per square meter (5–3 ft^2 per plant). In the bato bucket perlite system used in Anguilla at the CuisinArt Golf Resort Hydroponic Farm, the rows are 6 ft apart (1.8 m), and pots are spaced at 16-in. (40-cm) centers within the rows as described in Chapter 13. Two plants are set in each pot, and they are trained in a V-cordon system. This spacing is equivalent to 3.75 ft^2 per plant.

A 3-mo cropping period is used. In Florida, they recommend three crops per year (Lamb et al., 2001; Shaw et al., 2004). The plants start producing 5 wk after sowing and will produce for about 7–8 wk under tropical conditions.

For the first four to five nodes, remove all side shoots to permit strong initial vegetative growth before bearing fruit. Fruit should be left on the main stem after this level (Figure 16.32). Permit the side shoots to develop to two nodes on the next four to five nodes (Figure 16.33). Above that height, allow the side shoots to develop fully, pinching them when they get within 2 ft (60 cm) of the plant base. Remove all tendrils on the main stem and initial side shoots. Unlike European cucumbers, BA cucumbers are not trained in a renewal umbrella form. The BA cucumbers are not pinched when they reach the support cable, but their main stem is trained over the cable and allowed to come back down to within 2–3 ft (about 1 meter) of the floor. A plant clip is attached to the main vine and support cable as it comes over the cable (Figure 16.34). This is a very general description of training, as it will vary with your specific climatic conditions.

Harvestable fruit weighs between 115 and 120 g or four fruits per pound. If on the average we get eight fruits per plant per week, it is equivalent to 2 lb per plant per week (0.9 kg). While weekly production of European cucumbers averages between 2.5 and 3 lb (1.1–1.3 kg) per plant, the price of BA cucumbers is higher, so revenues may be somewhat better than for European cucumbers. Some reports (Shaw et al., 2004) indicate yields of 60 fruit per 4-mo season, harvesting for 11 wk.

The Beit-Alpha cucumbers have somewhat thicker skin than European cucumbers, but are still thin enough to not peel them. They do not need to be shrink-wrapped as do European cucumbers to conserve moisture. They will keep up to 14 d when stored at 50°F (10°C) with 95% RH (Sargent et al., 2001).

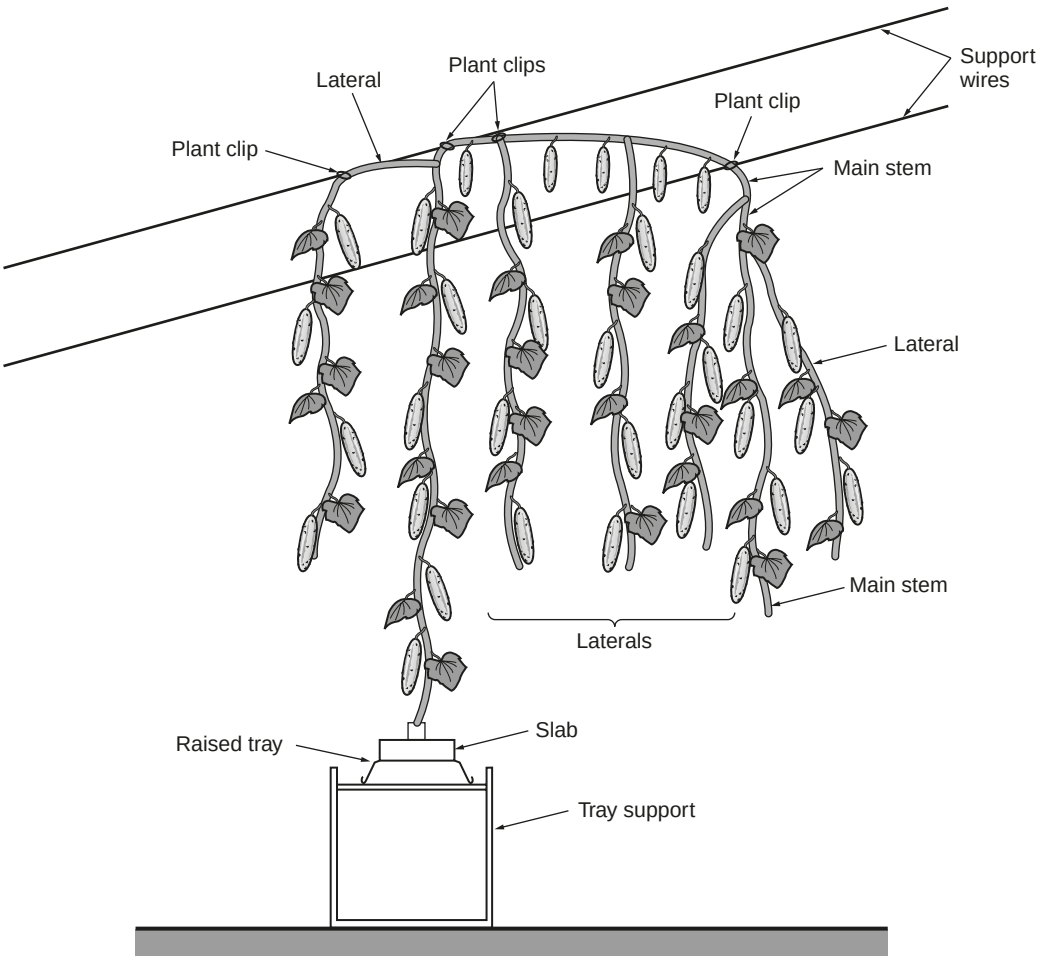

FIGURE 16.29 Modified umbrella cucumber training system. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

Researchers (Hochmuth et al., 2004) claim that BA cucumbers will tolerate both higher and lower temperatures of 90–100°F (35–40°C) and 60°F (15°C), respectively, compared to temperatures for European cucumbers, whose optimum ranges from 65–90°F (18–32°C).

Peppers are trained as two stems per plant in a V-cordon system supported by strings attached to overhead wires (Figures 16.35 through 16.39).

While the pepper plant starts out as a single stem, it soon bifurcates to form two stems and then continues to do so producing additional stems. Flower buds form at these division points on the stem (Figure 16.35). The flower in the first division of the stem is called a "crown" bud. Most greenhouse peppers are trimmed to two stems. Additional stems must be pruned to maintain a balance between vegetative growth and fruit development. To encourage vigorous initial vegetative growth capable of supporting later fruit production, flowers must be removed from the first and second stem layers (bifurcations) generally to a height of 16 in. (40 cm). After two stems have formed, remove all side shoots after the second leaf (Figures 16.36 and 16.37). This suckering is necessary every several weeks. The support string should be wound around the main stems in a clockwise direction every 2 wk or plant clips placed every 12 in. (30 cm).

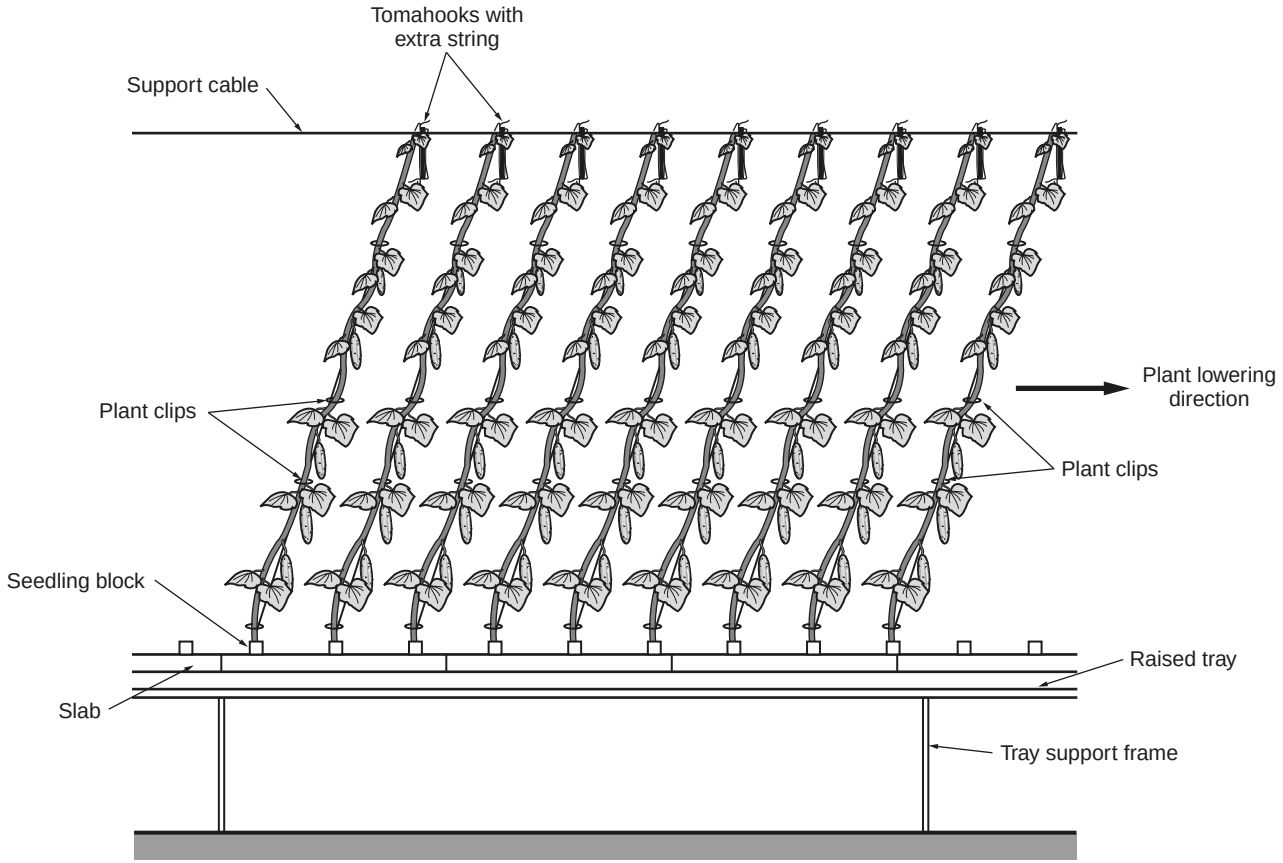

FIGURE 16.30 High-wire cucumber training. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

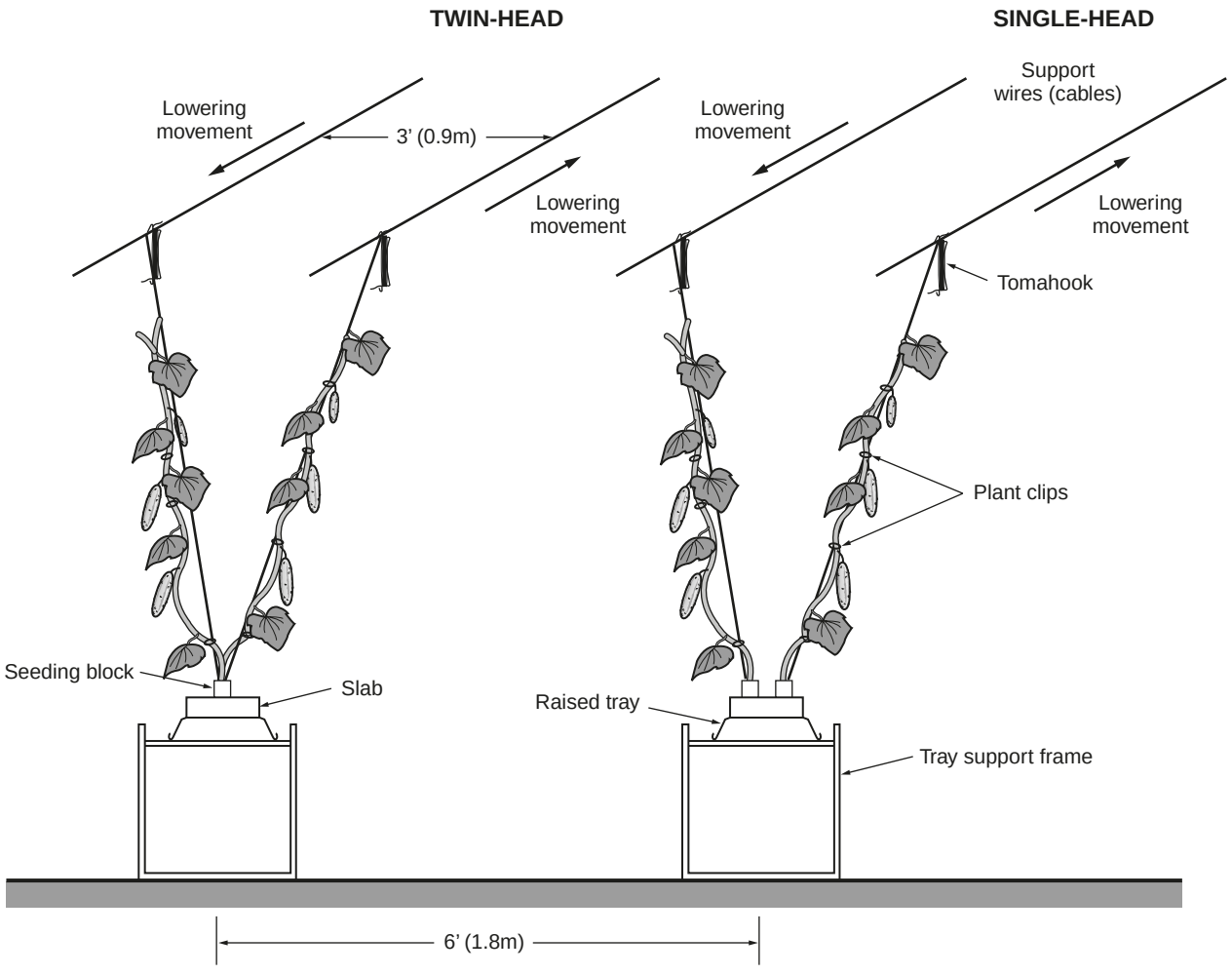

FIGURE 16.31 Twin-head V-cordon, high-wire training. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 16.32 Beit-Alpha (BA) cucumbers training.

Peppers grow slower than tomatoes or cucumbers. Generally, one crop per year is grown. The most common types of peppers grown are the four-lobed, blocky, sweet bell peppers (Figures 16.38 and 16.39). Red is the most popular color, making up 85%, followed by yellow (10%) and orange (5%). This mix of colors varies with market demand. Initially, these greenhouse peppers are green, ripening to the color of the variety. They are indeterminate (staking) varieties, so must be trained vertically in the greenhouse, similar to tomatoes. The plants grow to about 14–16 ft (4.3–4.9 m) in height during a single cropping cycle. In northerly latitudes, sow the seeds in mid-October, transplanting about 6 wk later, with harvesting beginning by March and continuing through mid-November. It takes 4 mo from seeding to first production. In southern latitudes, they can be sown in mid-July to get production by November, continuing until June of the following year. Annual yields should reach at least 23 kg/m^2 (4.7–5 lb/ft^2 or about 17–18 lb per plant).

As most greenhouses have gutters at least 4–5 m (13–16 ft) in height, it should not be necessary to lower peppers. They, however, can be lowered with care to prevent breaking of the very brittle stems. If the plants are lowered, remove three to four leaves first and lower them no more than 10–12 in. (25–30 cm). Unlike tomatoes, only a small number of leaves can be removed without stressing the plants.

Greenhouse grown eggplants *(Solanum melongena)*, also called aubergines, have become an important crop in Europe, and are now gaining popularity with the consumer in North America. There are a number of growers producing various types, but the traditional dark purple varieties are most in demand. Small "baby" eggplants are also gaining popularity as well as white and other varieties ("Graffiti") with white and purple stripes. Five Star Farms in Leamington, Ontario, Canada has 2.5 acres (1 ha) of purple, "Graffiti" and white baby eggplants. Windset Farms in British Columbia

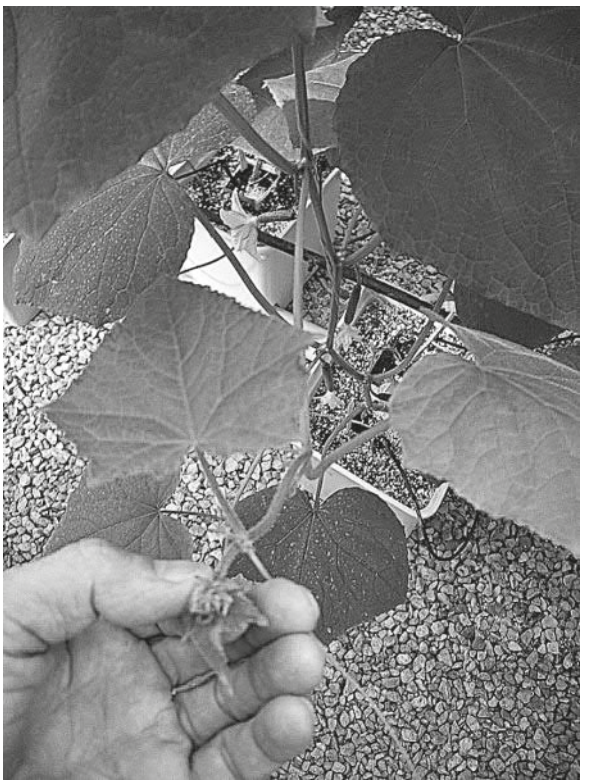

FIGURE 16.33 Pinch side shoots at two nodes on BA cucumbers. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

FIGURE 16.34 Bend growing point of BA cucumber over support cable and attach with a plant clip. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

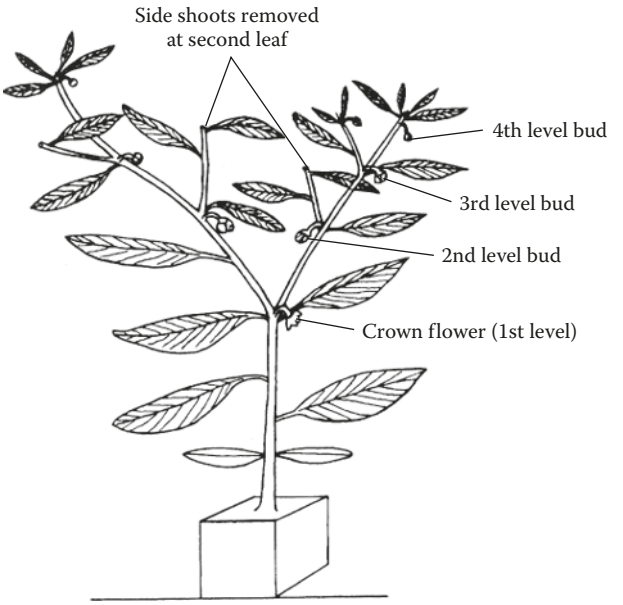

FIGURE 16.35 Position of flower buds and training of pepper plants in their early growth. (Courtesy of George Barile, Accurate Art, Inc., Holbrook, NY.)

FIGURE 16.36 Initial pruning of pepper. Note: The two main stems have the plant clips and string attached. The side shoot is in hand.

FIGURE 16.37 Side shoot to be removed at the second node. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

also grow a variety of baby eggplants. They are focusing on a purple variety, "Adagio," that has fruit weight of about 6–7 oz (175–200 g).

Selection of varieties is based upon size and color. The most popular of the larger varieties is the oval, purple (glossy violet) skin color with white interior. The fruit of oval varieties weighs from 350 to 400 g, while the elongated ones weigh from 200 to 300 g. A list of popular varieties is given in Table 16.4. For greenhouse culture indeterminate (staking) varieties must be used to best utilize the greenhouse space and maximize production.

The greenhouse structure must be able to support the weight of the plants as they are trained vertically similar to peppers and tomatoes. If the greenhouse superstructure is not strong enough for such support of the crop, a plant support system must be constructed inside the greenhouse of steel posts with braces set in concrete. The posts should have cross members at the top to attach the support cables. Plants are trained upward with string attached to the overhead cables. Plant clips are used to secure the plants to the strings. Gutter height of the greenhouse and/or support structures must be 12–14 ft (3.6–4.3 m) to contain the height of the plants on a 4-mo growth cycle. At that time they will reach about 12 ft in height.

In northern latitudes a crop cycle of two crops per year is practical, whereas, in more southerly latitudes it is better to use three crops annually. In northern latitudes, seed into rockwool cubes in mid-November. Transplant to rockwool blocks within 3–4 wk from sowing. After 7–8 wk from sowing transplant to the production system. In southern locations, transplanting to the growing area can be 1–2 wk shorter. Harvesting will begin in mid-February to early March. They take about 2.5 to 3 mo from sowing the seeds until first fruit production (slightly longer in northern latitudes with short day lengths during winter months).

FIGURE 16.38 Red bell peppers. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

In southern latitudes the grower must take advantage of the high late fall through winter prices. Seed in mid-August, transplant to the production area at the end of September for production to begin in early November. This production will continue for about 8–10 wk until the plants are removed at the end of January depending on productivity and height of the plants. This schedule is based upon three crops per year. Six weeks prior to removing the crop seed the next crop. The total cropping period is approximately 4 mo.

Eggplants are grafted onto disease-tolerant rootstock to boost vigor and protect against root pathogens. These same rootstocks, such as, "Maxifort" and "DR0141TX" are used for tomatoes. The eggplant scion seeds are sown 7–10 d before sowing the rootstocks. Green grafting is completed about 4 wk after sowing the eggplant "scion" seeds.

Grafted plants are transplanted into rockwool blocks immediately after healing. For non-grafted plants, at the first true-leaf stage separate and space the seedlings in their rockwool cubes to double the spacing. Place the seedlings on their sides in the tray when spacing them. That will give a 90° rotation to get better rooting and shortening of the stems when placed in the rockwool blocks. At 3–4 wk from sowing transplant to rockwool blocks of 7.5 cm x 10 cm. Before transplanting, soak the blocks with full strength nutrient solution of EC 1.5 to 2.0 mS at 23°C. Ebb-and-flow irrigation from the bottom is better than overhead watering. Frequency of watering depends on the local weather conditions. Maintain air temperatures at 21–23°C (70–73°F) during the day and 20–21°C (68–70°F) at night. Refer to Table 16.1 for optimum night and day temperatures for the various stages of growth.

FIGURE 16.39 Yellow bell peppers in perlite bato buckets. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

Optimum lighting during seedling stage is 12–16 moles/m^2/day for 18–20 h per day. Do not permit the plants to get overcrowded. Space them apart as soon as the leaves start to overlap. When first transplanting the seedlings to the blocks, space the blocks in a checkerboard pattern to permit more light (six blocks per tray). At 30 d space the plants to 20 plants/m^2 and keep block temperatures at 21–22°C (70–72°F). Carbon dioxide enrichment of 800 ppm is beneficial. Seedlings are transplanted to the greenhouse production area when they are between 6 and 7 wk old. The EC of the blocks now should be from 3.0 to 3.5 mS.

Optimum lighting during production is 25–50 moles/m^2/day for 18–20 h per day. Under full fruit load, maintain temperatures from 20–22°C (68–72°F) during the day and 17–19°C (63–66°F) at night. A plant density, similar to tomatoes, of 3.3 to 3.5 plants/m^2 of greenhouse area is recommended. As the plants are trained to two stems (heads) each this is a density of 6.6 to 7 stems/m^2. The spacing depends on the layout of the greenhouse and the growing system.

When growing in perlite in bato buckets, use two plants per bucket and space the buckets 40 cm apart alternated on each side of a 2-in. diameter drain pipe. The rows are 1.8 m (6 ft) apart and the plants are trained in a V-cordon fashion to the overhead wires similar to peppers (Figure 16.10). Each plant is grown with two stems. Within each pot of two plants, one plant with its two stems is supported by one wire and the other plant is leaned toward the other support wire. This configuration in effect forms two rows of plants from one row of pots.

FIGURE 16.40 Eggplant at 2 mo from sowing pruned to two main stems. Note: The strong upper flower and the lower smaller, weak flowers. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

In coco coir, sawdust, perlite, or rockwool cultures using bags or slabs, the bags or slabs may be set in two rows or one. If two rows (double) are used, place 3 plants per bag or slab, whereas, in a single row locate 5 plants per bag or slab. Most growers use the single row method with more plants and V-cordon them overhead. Spacing between two single rows is 40 cm and 1.46 m between the drainage/irrigation lines. Slabs are spaced 23 cm apart within each row if the slabs are 100 cm in length. For a single row system rows are 1.8 m (6 ft) apart and the slabs placed together end-to-end within the row. This vertical V-cordon training system is very similar to peppers. With the V-cordon training to the upper support cables the final plant density regardless of the row configuration is from 3.3 to 3.5 plants per square meter of greenhouse floor area.

Eggplants grow faster than peppers and can reach a height of 16 ft (5 m) during a season. They are trained to two stems per plant very similar to peppers. They are allowed to bifurcate early similar to peppers by selecting the two most vigorous stems (Figure 16.40). Remove all side shoots up to 1 m in height. Side shoots are removed at the second node allowing one fruit to develop per side shoot (Figure 16.41). Remove lower leaves (maximum of 3) every two weeks. Place plant clips about every 12 in. (30 cm) along the main stem under a strong leaf to attach them to the support string.

Allow two leaves, with no more than one flower on the side shoots (laterals) before cutting the tip. Eggplants are parthenocarpic, so develop good fruit without seed. However, pollination will improve flower set and yield. Pollination can be done by bumble bees or with a special vibrator called a “Petal Tickler” (Figure 16.45). If more than one flower forms on a truss, the stronger one

FIGURE 16.41 Side shoots are cut at the second node. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

FIGURE 16.42 Lowering of eggplants when they reach the support cables. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

will be larger than the other weaker one(s) (Figures 16.40 and 16.47). Remove all the weak, smaller flowers, so that the strong flower will produce large fruit. Allow only one fruit on a side shoot. Secondary lateral shoots that develop on the side shoots should be pinched.

If the greenhouse gutters are less than 16 ft (5 m) the plants can be lowered; however, like peppers they get stressed during this process and often loose lower leaves and the plants break easily. In

FIGURE 16.43 The stems are lowered, and side shoots grow at the base. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

Anguilla the eggplants began being lowered after about 4 mo from sowing (Figure 16.42). As they continued growing to about 12–13 ft (3.6–4 m) (Figure 16.43), the plants began losing lower leaves. The tops were cut at about 1 ft (30 cm) above the support wire to permit them to develop several fruit above the wire.

In a trial, the main stem was cut back to the base and two side shoots allowed to form as new plants (Figure 16.44). While the side shoots grew well, smaller fruits were produced than the original plants. It was concluded that it is better to replace the crop once the plants grow above the support wires to avoid the difficulty of lowering the plants. This resulted in a three-crop system annually. A three-crop system should be used if the greenhouse gutters are less than 4 m in height.

With a low gutter greenhouse using the three-crop annual growing cycle, when the plants reach within 50–60 cm of the support wire, allow one to two additional side shoots to form. The number of side shoots allowed to grow is a function of the plant vigor. For a more vigorous plant, permit two side shoots to grow. This practice will slow the growing speed to the wire.

Be careful to maintain the main stem strong. If by mistake or other damage it should be terminated, allow a strong side shoot to take over as the main leader.

FIGURE 16.44 New shoots forming at the base after the old main stems are cut back. (From CuisinArt Golf Resort & Spa, Anguilla. With permission.)

16.14 POLLINATION

Tomatoes, peppers, and eggplants are normally wind pollinated or pollinated by bees when grown outside. In greenhouses, however, air movement is insufficient for flowers to pollinate themselves. Vibration of the tomato flower clusters is essential for good pollination in a greenhouse. This can be done by tapping the flowers with a stick, your fingers, or an electric vibrator such as an electric toothbrush. A very useful vibrator is the "Petal Tickler." It is a long vibrator that has high-frequency vibration to effectively dislodge the pollen of the flowers. The vibrator is momentarily held lightly against the flower-cluster branch (Figure 16.45). If environmental conditions are favorable and the flower is receptive, the fine yellow pollen can be seen flowing from the flower upon vibration.

Pollination must be done while the flowers are in a receptive state. This is indicated by their petals curling back in the case of tomatoes, and to a lesser degree in eggplants, the stamens are very prominent (Figures 16.46 and 16.47). Plants should be pollinated at least every other day, since blossoms remain receptive for about 2 d. Pollinating should be done between 11:00 A.M. and 3:00 P.M. under sunny conditions for best results. Research has shown that RH of 70% is optimum for pollination, fruit set, and fruit development. High humidity keeps pollen damp and sticky, except around midday, and lessens the chances of sufficient pollen transfer from anthers to stigma. Too dry conditions (RH less than 60–65%) cause desiccation of pollen.

FIGURE 16.45 "Petal Tickler" used to pollinate tomato flowers.

Greenhouse temperatures should not fall below 60°F (15°C) at night nor exceed 85°F (29°C) during the day. At higher or lower temperatures, pollen germination and pollen tube growth are greatly reduced. Chemical growth regulators can be used to induce fruit development under lower-than-optimum temperatures, but these fruits are usually seedless. Open locules and thin outer walls may make the fruit soft and greatly reduce their quality.

If pollination has been done correctly, small beadlike fruit will develop within a week or so. This is called fruit set. When young plants produce their first trusses, pollinate each day until fruit set is visible. It is important to get the fruit set on these first trusses, as it throws the plant into a reproductive state, which favors greater flower and fruit production as the plant ages. After the first few trusses have set, pollinating can be done every other day.

In the past, pollination of tomatoes was done by using vibrators. Pollination of 5 acres (2 ha) of greenhouse tomatoes can take two people full time. Use of bumble bees (*Bombus sp.*) is now the accepted form of pollination of greenhouse tomatoes. It is important to maintain the correct population levels of bumble bees, as overpopulation may result in the bees overworking the tomato flowers. This is particularly true with peppers, which require a lower population so they will not aggressively enter the blossoms and as a result cause a zipper-pattern scar on the fruit.

Bumble-bee hives, costing about $350 each, are available from a number of suppliers (Appendix 5) (Figure 16.48). The population of one hive is sufficient to work one-half acre (0.2 ha) of tomatoes. A 66% sugar-water (by weight) solution with a preservative provides food for the bees, as the tomato flowers do not provide nectar. A supply reservoir sits above the hive. The bees form a round

FIGURE 16.46 Tomato flower cluster with receptive flowers.

FIGURE 16.47 Receptive eggplant flower.

FIGURE 16.48 Bumble bee hives for pollination. (From Houweling's Group, Camarillo, CA. With permission.)

hive inside the box container. A Plexiglas plastic top under the reservoir allows the grower to visually observe the progress of the bee population. A slide stopper is positioned across the entrance to the hive to contain the bees when examining the inside of the hive.

The species of bumble bee is dependent on which are indigenous to the area they are applied. The longevity of the hive is highly dependent on active workers, a viable queen, and developing brood. Optimum temperatures for hives must be less than 85°F (30°C), or the hives shut down. Locate the opening of the hive toward a wall, walkway, or post to assist the bees to find it, as shown in Figure 16.48. The number of hives required for effective pollination ranges from 5 to 7.5 per hectare or 2 to 3 per acre. This is based on hive efficiency (activity of queen). Monitor the pollination by determining the percentage of bruised corolla (all petals together) and sample the blossoms at the postreceptive (folding-up of petals) stage, which should show 90–100% bruising. This indicates the number of flowers worked by the bees. Examination of the sugar-water consumption every 2–3 d should reveal that it is being depleted at a constant or increasing rate.

European and BA cucumbers, unlike the regular North American seeded cucumbers, do not require pollinating to set fruit, and the fruits are therefore seedless. Pollination may occur by bees and from male flowers (Figure 16.49) on the same or neighboring plants in the greenhouse. Pollination causes seeds to form, and the fruits become clubbed at the end and develop a bitter taste. To prevent pollination, bees must not be allowed to enter the greenhouse, and male blossoms should

FIGURE 16.49 Male flower on European cucumber. Note: No small fruit exists behind the blossom.

FIGURE 16.50 Female European cucumber flower.

be removed from the plants as soon as they develop. Now, all-female varieties have been developed so the male blossoms seldom develop. However, periodically male plants develop initially and may turn to female as they grow. Remove the male flowers from these plants. The female flower is very distinct with its very small fruit behind the flower (Figure 16.50).

16.15 PHYSIOLOGICAL DISORDERS

Hydroponics has many advantages, but it does not free the grower from the need for alertness in dealing with many physiological disorders common to all forms of food production. Physiological disorders are those fruit-quality defects caused by undesirable temperatures, faulty nutrition, or improper irrigation. Some varieties are more susceptible than others to some of these disorders. Because we are using tomatoes, peppers, eggplants, and cucumbers as examples, we will present as a reference source several disorders common to those fruits.

1. *Blossom-end rot (BER) (tomatoes, peppers).* This disorder appears as a brown, sunburned, leathery tissue at the blossom end of the fruit (Figure 16.51). In the early stages, the affected area will have a green, water-soaked appearance. While the cause of BER is a low supply of calcium to the fruit, the indirect cause is plant stress. This stress may be due to (a) low soil (medium) moisture, (b) excess soluble salts in the growing medium, (c) high

FIGURE 16.51 Blossom-end rot (BER) of tomatoes.

FIGURE 16.52 Fruit cracking of tomatoes.

rates of transpiration, and (d) high soil moisture in heavy soils, which leads to poor root aeration. BER, assuming that calcium levels are sufficient, may be due to low RH (50% or lower) combined with high temperatures (28°C or 82°F or higher). These conditions cause a rapid increase in transpiration that results in high water loss from the leaves, and consequently the calcium travels in the water to the leaves and not to the fruit. Also, high RH in excess of 90% causing insufficient root oxygenation will decrease transpiration and calcium uptake.

BER may be reduced by maintaining night and day RH at 65–75% and 75–85%, respectively. Provide good oxygenation to plant roots. Allow more fruit to develop on the first two trusses. Do not remove fruit affected with BER. Apply shade during high light periods of the day. Maintain a good balance between vegetative and generative phases. Researchers claim that the most critical period is about 2 wk after flower development when the rate of fruit growth is greatest (El-Gizawy et al., 1986).

2. *Fruit cracking (tomatoes, peppers, eggplants).* Symptoms are cracks radiating from the stem, almost always on maturing fruit, at any time during ripening (Figure 16.52). This is usually caused by water deficit and excessively high fruit temperatures followed by a sudden change in moisture supply to the plants. Prevention is by avoidance of high fruit temperatures and maintenance of uniform soil (medium) moisture conditions. Start irrigation cycles from 1 to 2 h after sunrise and the last one 1 h before sunset. One may find that a night irrigation cycle could help.
3. *Blotchy ripening (tomatoes).* This is uneven coloring of the fruit wall in the form of irregular, light green to colorless areas, with brown areas in the vascular tissue inside the fruit. It is associated with low light intensity, cool temperatures, high soil moisture, high nitrogen, and low potassium. It can be avoided under low light intensity conditions by less frequent irrigation cycles and less fertilizer (especially nitrogen).
4. *Green shoulder, sunscald (tomatoes, peppers, eggplants).* These disorders are associated with high temperature or high light intensity (Figure 16.53). Avoid removing leaves that offer protection to fruit clusters during the spring and summer months when sunlight is intense, and

FIGURE 16.53 Sunscald on pepper.

FIGURE 16.54 Catfacing of tomato.

keep greenhouse temperatures down. Maintain a good leaf canopy, and use shading under high light. Peppers are particularly susceptible to sun scald.

5. *Misshapen fruit, roughness, and catfacing (tomatoes, peppers).* This is radial wrinkling of the fruit shoulders and walls and fruit-shape distortion due to protuberances and indentations (Figures 16.54 and 16.55). This is caused by poor pollination and environmental factors such as low temperatures and high RH, which cause the flower parts to develop abnormally. Low

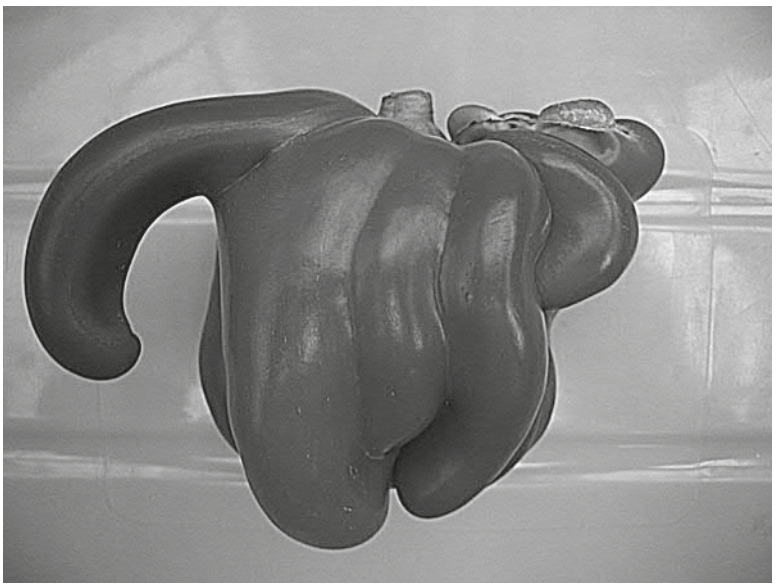

FIGURE 16.55 Catfacing of pepper.

FIGURE 16.56 Crooking of cucumber fruit.

RH during flower set can also contribute to this condition. Remove misshapen fruit early in its development.

6. *Crooking (cucumbers).* This is excessive fruit curvature caused by a slowdown in growth (Figure 16.56). It can be caused by a leaf or stem interfering with the growth of the young fruit or the sticking of a flower petal on the spines of a leaf, stem or another young fruit. Also, tendrils can attach to the young fruit and cause crooking. Other causes include mechanical damage, chilling injury, thrips injury, and gummy stem blight in the fruit. Adverse

temperature, excessive substrate moisture, and poor nutrition have also been suggested as causes. Remove severely curved fruit from the plant immediately.

7. *Fruit abortion (cucumbers).* Abortion of fruit occurs when very young if fruit load is too high, under low light levels, and/or poor root development. The most common cause is poor training of the plant and more than four to five fruits forming on the plant at the same time.

16.16 DISEASES AND INSECTS

Since the control of diseases and insects is very specific, only a brief description of the most common problems are given here. For additional information see articles listed in the bibliography and books having colored photographs (Blanchard, 1997).

16.16.1 Some Common Tomato Diseases

1. *Leaf mold (Cladosporium).* This starts as a small gray spot on the lower side of the leaf and spreads until a definite pale area also develops on the upper surface. Additional infection sites develop, and the initially small spots expand. The basic control measure is sanitation within the greenhouse and careful ventilation and temperature control to prevent high humidity. Some fungicide sprays can be helpful.
2. *Wilt (Fusarium and Verticillium).* Initially, plants wilt on hot days, then eventually they wilt all the time and the leaves become yellow. If the plant is cut just above the soil surface, a darkened ring is visible inside the outer green layer of cells. No spray or cultural treatment will control these diseases. They can be controlled through sterilization of the growing medium and use of resistant or tolerant varieties. Most growers now use grafted tomatoes and peppers to impart resistance to the scion cultivar against these organisms. All cultivars are given a code as to which disease organisms they have resistance against. A good summary of resistance codes is available through Enza Zaden's website, www.enzazaden.com. Whenever one searches for a cultivar it will be followed by the codes to which it is resistant. There are two levels of resistance, high resistance (HR) and intermediate resistance (IR). Those having HR restrict the growth and development of the pest or pathogen. They may exhibit some symptoms or damage under heavy pest or pathogen pressure. Intermediate resistant varieties, while they do restrict the growth and development of the pest or pathogen, may express greater symptoms or damage compared to highly resistant varieties. Susceptible varieties are unable to restrict growth or development of pests or pathogens and therefore will suffer significant damage from them.

   Some varieties are specifically resistant to certain strains of pathogens and not others. This is indicated by the code. The same codes are used for the same pathogens or pests regardless whether the plant is a tomato, pepper, cucumber, eggplant, or lettuce, as some are common to a number of different crops.

   A few typical codes are *Fusarium oxysporum f. sp. cucumerinum* (Foc) – cucumber *Fusarium*; *Fusarium oxysporum f. sp. lycopersici* (Fol) – tomato *Fusarium*; *Verticillium dahliae* (Vd) – *Verticillium* wilt of tomato; *Meloidogyne arenaria* (Ma) – root-knot nematode in tomatoes and peppers; *Cucumber mosaic virus* (CMV) – cucumber mosaic; *Tomato mosaic virus* (ToMV) – tomato mosaic.
3. *Early blight and leaf spot (Alternaria and Septoria).* These cause discolored or dead spots on the leaves. Early blight has dark rings on a brown background. Leaf spot has small black dots on the affected area. Both organisms attack the oldest leaves first and cause severe defoliation of the lower part of the plant. Proper ventilation and removal of lower senescing leaves to improve air circulation and reduce RH helps reduce the disease.
4. *Gray mold (Botrytis).* Under high humidity conditions, fungal spores infect wounds such as leaf scars, and a watery rot and fluffy gray growth forms over the affected area. The disease

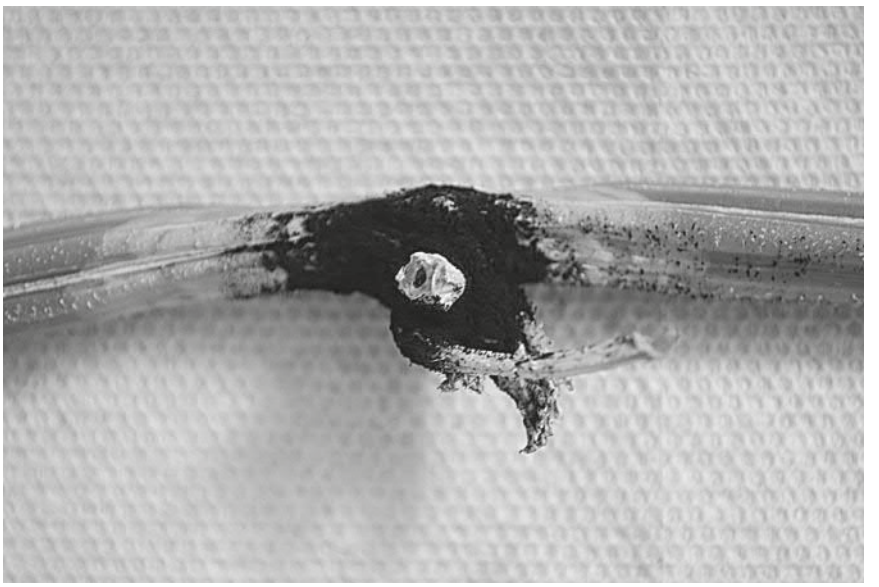

FIGURE 16.57 *Botrytis* on tomato stem.

may develop along the stem for several inches and eventually girdle it, killing the plant (Figure 16.57). Proper ventilation to reduce the RH will prevent the spread of the disease. Remove infected plants immediately. Affected areas at early stages of infection can be scraped and covered with a fungicide (Ferbam) paste, or the plant can be sprayed with Ferbam.

5. *Virus (tobacco mosaic virus, TMV).* Several viruses will attack tomatoes. TMV is the most common, causing distortion of the leaves and stunting of growth, with resultant yield reductions. Plant juice containing the virus is spread by sucking insects or on the hands or tools of the people working with the crop. Sanitation, control of sucking insects, and no smoking (TMV is present in tobacco) in greenhouses will help avoid infection. At present, most tomato varieties have TMV resistance or tolerance, as is specified by the code ToMV by seed houses. This obviates the need for other TMV protection.

16.16.2 Some Common Cucumber Diseases

1. *Powdery mildew.* Small snow-white spots initially appear on the upper surface of the leaves. They quickly spread in size and to other leaves (Figure 16.58). Proper sanitation and adequate ventilation are the primary control measures. Chemical control is also possible. Many growers use elemental sulfur vaporized by heating to form a smokelike cloud in the greenhouse overnight.
2. *Cucumber mosaic virus (CMV).* Some of the same strains of virus found on tomatoes also infect cucumbers. The affected leaves are dwarfed or become long and narrow. No control measure other than prevention through sanitation is known. Control of sucking insects would prevent spreading of the virus to other plants. Now, many cucumber cultivars have resistance to this disease bred into them and are indicated with the code CMV after the variety name.
3. *Wilt (Fusarium).* This is the same wilt disease as found commonly in tomatoes. Proper sterilization of the growing medium between crops and sanitation are the only control measures besides finding varieties resistant to the disease. Before transplanting, it is important to pretreat the substrate with a beneficial fungus such as RootShield (*Trichoderma harzianum,* strain T-22) or Obtego (*Trichoderma asperellum*, strain ICC 012) and *Tricoderma gamsii* (strain ICC 080) as a drench or incorporation of a granular form into the substrate. This fungus

FIGURE 16.58 Powdery mildew on cucumbers.

protects against *Pythium*, *Fusarium*, *Rhizoctonia*, *Sclerotinia*, *Thielaviopsis*, *Verticillim*, and *Cylindrocladium* root disease organisms. It attaches to plant roots and releases an enzyme that dissolves the cell walls of these fungal pathogens. RootShield granules are blended into the substrate at a rate of 1.25–1.5 lb/yd^3 (0.57–0.68 kg/0.76 m^3). RootShield WP (wettable powder) is applied as a drench at a rate of 4.5 oz/100 gal (128 g/378 L). It can be applied through low-pressure nozzles, overhead boom sprayers or sprinklers, or sub-irrigation. For detailed information refer to BioWorks website, www.bioworksinc.com.

4. *Gray mold (Botrytis).* The symptoms and control measure are the same as for tomatoes.
5. *Gummy stem blight (Didymella bryoniae).* Tan-colored lesions appear on petiole stubs and the base of the main stem (Figure 16.59). It also infects flowers and developing fruit, causing shriveled fruit at the flower end and internal browning of tissue. Avoid condensation on plants and guttation (Figure 16.60) by adequate ventilation. Guttation is the escape of water along the leaf margins through special large cells, usually in the early morning when root pressure is high and RH is high (VPD is low). Do not leave stubs when pruning, and disinfect pruning knives. Remove crop debris and bury away from the greenhouse. Apply fungicide sprays of Rovral 50 WP or Benlate 50 WP and Manzate 200 at 4- or 7-d intervals, respectively, when infection appears or during high humidity and low light levels. Do not apply within 5 d of harvest. Follow rate and application directions of the fungicide label.

The following are other disorders or damage that may occur:

1. *Pesticide burn*. Often when spraying during high temperatures or under full sunlight without a shading system, even the mildest of bioagents (natural pesticides) can burn plants. The burn will start as a water sinking of the tissue and will be followed with drying and or bleached tissue of leaves (Figure 16.61). This is particularly evident with large, soft-tissue leaves of cucumbers.
2. *Guttation*. This is drops of liquid at the tips and margins of the leaves (Figure 16.60) as mentioned above. This occurs during the night as high root pressure pushes water up from the roots to the leaves and stems, especially under high RH. At night, the stomates are closed and transpiration stops. Specialized structures called hydathodes located at the tips and margins of

FIGURE 16.59 Gummy stem blight on stem of cucumber.

FIGURE 16.60 Guttation on cucumber leaf.

FIGURE 16.61 Pesticide burn on cucumber leaf.

FIGURE 16.62 Edema on cape gooseberry leaves.

the leaves open, allowing the excess water accumulating in the leaves to escape, forming water droplets. When the water evaporates later in the morning as RH falls and ventilation is present, a film of dried sugars and minerals remain at the edges of the leaves.

3. *Edema*. Similar to guttation, this is a physiological disorder that develops when the plant absorbs water faster than it is lost by respiration. This excess moisture in the plant builds up and causes swellings on the leaves (Figure 16.62). They initially form as pale-green blisters or bumps on the underside of the leaves and progressively swell through to the upper leaf

surface. Do not mistake them for some fungal rusts. The cells eventually form larger yellow to brownish spots. This disorder does not affect fruit production in tomatoes, but eventually can damage the leaf area sufficiently to reduce yields if it continues for some time. Conditions that favor it are cloudy weather with high humidity and cool temperatures. To prevent it, cut back on watering cycles during periods of dull weather, increase light if possible by supplementary lighting, and increase ventilation in the greenhouse and around the plants by removing lower leaves on tomatoes. Plants will recover from edema under more favorable growing conditions.

16.16.3 Insects

Biological control of insect pests is now widely accepted in the greenhouse industry. A number of companies (Appendix 2) sell these biological agents. Biological control refers to the use of living organisms to control other living pest organisms. Integrated pest management (IPM) is the use of beneficial insects and natural pesticides as a pest management program to control pests. There are a number of very good websites that give details on indentification of pests and the natural organisms used in their control as outlined in Appendices 2 and 5. An excellent identification reference book is by Malais and Ravensberg (1992).

In IPM, pests can be controlled in a sustainable fashion by using biological, cultural, physical, and chemical methods that minimize environmental risks. For the program to be successful, the crops must be monitored for pests at least once a week using sticky cards (Figure 16.63). Identify and

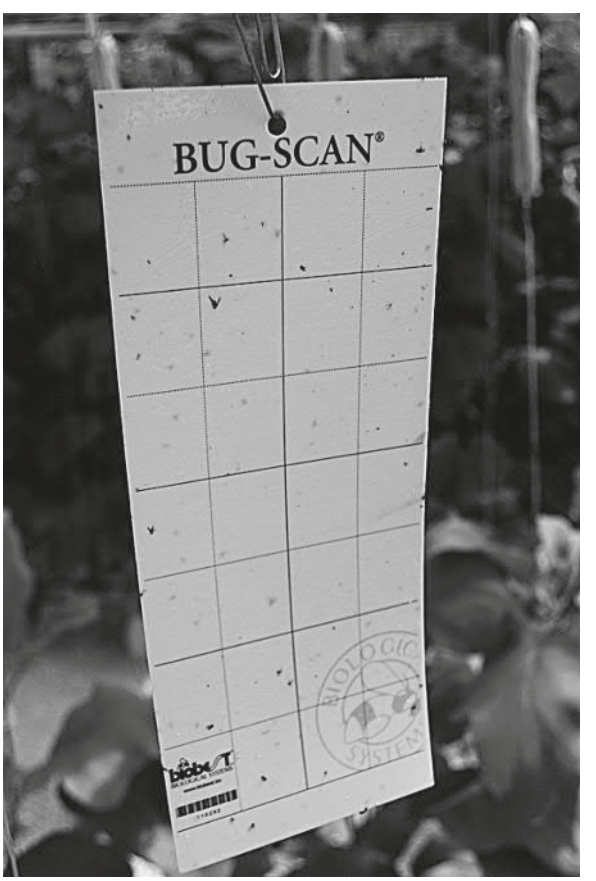

FIGURE 16.63 "Bug-Scan" sticky card.

record the pests present on the cards to determine their population dynamics. Set a threshold level at which numbers of any pest warrant action with the IPM program by introducing or reintroducing biological agents to control the pests. This balance between pest and beneficial insect populations must be kept in check by weekly monitoring and identification and introduction of additional beneficial agents as necessary.

There are a number of advantages to using biological control agents. Pests cannot build up resistance against biological agents as easily as they can with pesticides. The cost of biological control is less than that of pesticides. There is no fear of phytotoxicity or persistence of chemicals potentially hazardous to human health. Generally, biological control does not completely eliminate the pest, as a certain level of pest population is necessary to sustain the predator population. For this reason, emphasis is on integrated control, using biological control agents with cultural and chemical control measures. The objective is not complete pest elimination, but pest management, whereby pest populations are maintained at a level below any significant plant damage.

With an IPM program, only certain pesticides must be used, which do not harm the predatory agents. However, highly infested areas may be spot treated by other more poisonous pesticides if pest populations cannot be controlled by the biological agents. Once such infestations are reduced, the use of these chemicals should be restricted. Pesticides such as insecticidal soaps, insect growth regulators or hormones, yellow sticky traps, and bacterial or fungi insecticides may be used with the biological agents without harming them.

The grower must check with government agencies and companies selling biological agents to determine which pesticides may be used without harming the specific predators in their IPM program. For example, if a program of mite control using the predatory mite *Phytoseiulus persimilis* has been introduced into the greenhouse, outbreaks of the two-spotted mite may be controlled using Agri-Mek 0.15 EC (Abamectin 2%), which is harmless to the predatory mite. Yellow sticky traps (Figure 16.63) may be used to monitor pests in the greenhouse. These sticky cards (Bug-Scan) are available commercially from greenhouse suppliers such as Biobest Biological Systems (www.biobest.be), who, like Koppert B.V., supply biological agents and bumble bees for pollination. The Bug-Scan cards have a grid on one side where one can identify and count the insects.

Many of the biological supply houses such as Koppert B.V. (www.koppert.com) will provide a complete pest management program for the grower, in which they monitor and introduce various biological agents to incorporate the IPM program into the greenhouse operation. In this way, their consultants plan, initiate, monitor, and manage the program in its entirety.

1. *Whitefly (Trialeurodes vaporariorum – glasshouse whitefly and Bemisia tabaci – tobacco whitefly).* The whitefly life cycle is 4–5 wk, during which time it undergoes a number of molts in the nymph stage as shown in Figure 16.64. This is the most common pest in the greenhouse tomato crop. It is usually located on the undersides of the leaves. When at rest on a leaf, its triangular white body makes it easy to identify. The insect secretes a sticky substance on the leaves and fruit, in which a black fungus later grows, making it necessary to clean the fruit before marketing. Numerous pesticides such as pyrethrin, Azatin, M-Pede, Pyganic, Fulfil, BotaniGard, and Provado can be used in the IPM program with the beneficial insects to control the whiteflies. However, the insects quickly build up resistance, making it necessary to use different pesticides to obtain reasonable control.

Whitefly is also a common pest on cucumbers and peppers.

Biological control may be achieved by the use of a number of beneficial insects that predatorize or parasitize the pests. These, such as the chalcidoid wasp *Encarsia formosa* (En-Strip; Koppert product name), *Erectmocerus eremicus* (Ercal), *Amblyselus swirskii* (Swirski-Mite), and *Delphastus catalinae* (Delphibug) (Figure 16.65), are some biological control agents available from bioagents suppliers such as Koppert and Biobest. In the case of the wasps, the female lays eggs in the whitefly larvae and also eat early larval stages of the whitefly. The parasitic grub feeds within the larva, which turns black within 2 wk, providing an easy method of determining the success of the predator. Successful control is temperature and humidity dependent, as the predators/parasites have specific

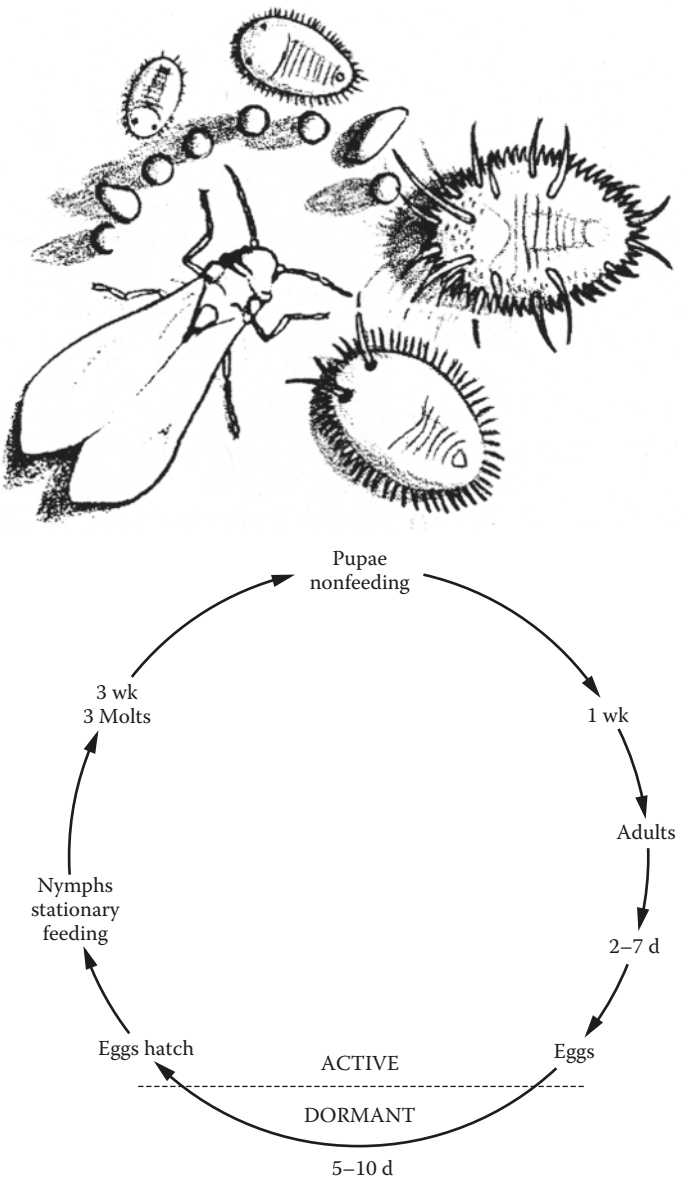

FIGURE 16.64 Life cycle of whitefly. (From J.R. Baker, North Carolina Agricultural Extension Service, Raleigh, NC. With permission.)

optimum temperature and RH ranges under which they reproduce. Optimum conditions, for example, for *E. formosa* to reproduce are a mean temperature of 23°C (73°F) and an RH not exceeding 70%. For specific conditions in a particular area consult with the suppliers as to which of the organisms will best reproduce and control the whitefly. It was found that *Eretmocerus eremicus* (Ercal) and *Amblyseius swirskii* (Swirski-Mite) are more suitable for higher temperatures and humidities. *Encarsia* and *Eretmocerus* are purchased as pupae stuck to paper strips (Figures 16.65 and 16.66), which are hung on plants in the greenhouse (Figure 16.67). Each card contains the black pupae from which the parasite emerges. As soon as the first whiteflies are found, a program of repeated introductions of the predators/parasites must be initiated.

FIGURE 16.65 Biological control agents.

FIGURE 16.66 Ercal has *Eretmocerus eremicus* pupae stuck to paper strips.

FIGURE 16.67 Paper strip with *Encarsia* pupae.

To use *E. formosa* successfully, follow these steps:

i. Do not use residual pesticides for a month before introduction.
ii. Reduce existing whitefly populations using insecticidal soap or insect hormones, to an average of less than one adult per upper leaf.
iii. Adjust temperature and humidity to 23–27°C (73–81°F) and 50–70%, respectively.
iv. Introduce *Encarsia* at a rate of 10 per square meter (1 per square foot) of planted area or one to five per infested plant.
v. Reintroduce *Encarsia* weekly for up to nine introductions.
vi. Monitor plants weekly for the number of whitefly and black scales.

This is a general guideline, so be sure to check with the supplier on the specific procedures for the organisms to be employed.

Several parasitic fungi, *Verticillium lecanii-m* (Mycotal) and *Achersonia aleyroidis*, are available commercially for controlling whitefly. They are safe to use with *E. formosa*.

In recent years, the sweet potato whitefly *(Bemisia tobaci)* has become a more common pest in greenhouses. A new predator very effective on these whiteflies is the black bug *(Delphastus catalinae* or *D. pusillus)* larvae and adults that can eat as many as 160 whitefly eggs per day. Under higher temperatures, in excess of 80°F (27°C), *E. eremicus*, a parasitic wasp, is more effective in

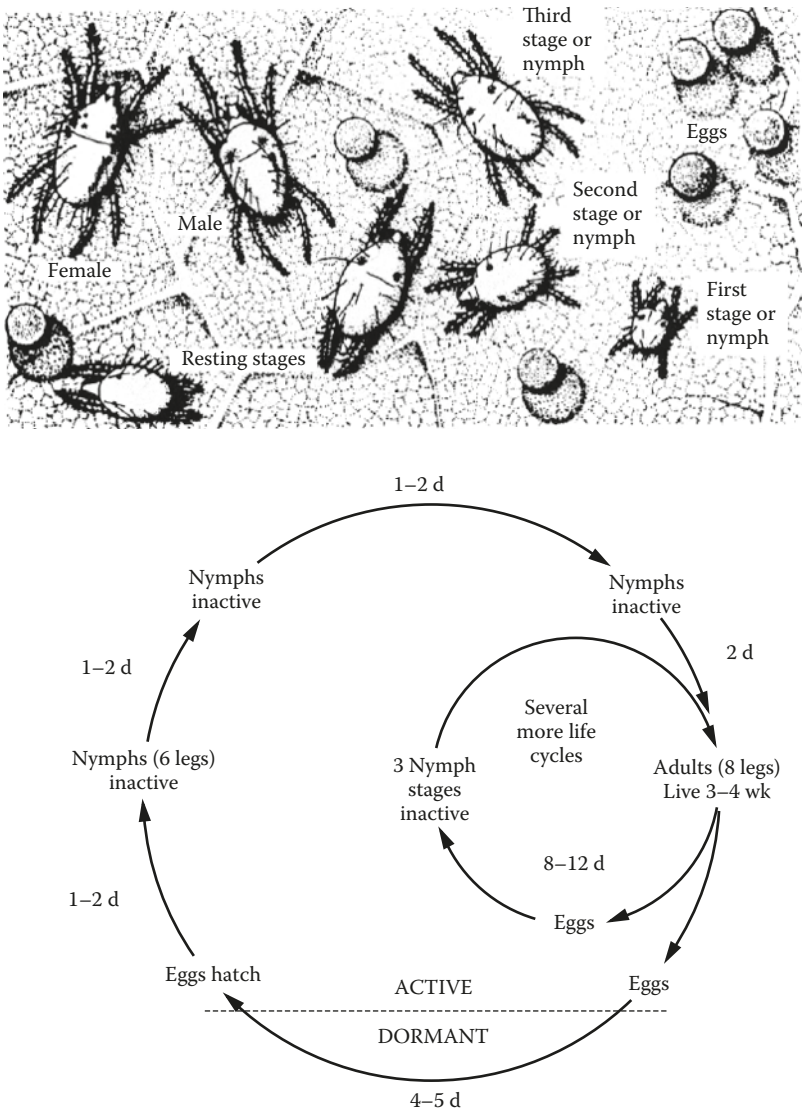

FIGURE 16.68 Life cycle of two-spotted spider mite. (From J.R. Baker, North Carolina Agricultural Extension Service, Raleigh, NC. With permission.)

controlling both the greenhouse and sweet potato whiteflies in the second and third larval stages. A mix of *E. formosa* and *E. eremicus* (Enermix) is available to control the whitefly in its second to fourth larval stages.

2. *Two-spotted spider mite (Tetranychus urticae).* Mites are closely related to spiders and ticks, having four pairs of legs, unlike insects, which have three pairs of legs. Their life cycle goes through a number of nymph stages, as indicated in Figure 16.68. Their life cycle is from 10 to 14 d, depending on temperature. At 26°C (80°F) the cycle is shortened to 10 d, whereas at lower temperatures the cycle may be up to 2 mo. Low RH also favors their development. Misting plants frequently during dry periods will discourage spider mites, as they dislike high humidity.

This pest is particularly common on cucumbers. A webbing appearance on the undersides of leaves indicates an already heavy infestation. A magnifying glass is needed to observe the mite closely in order to see the dark-colored spot on each side of its body. The mite causes a yellowing of leaves, starting as very small yellow pin-sized dots that coalesce to eventually form a very characteristic bronzed appearance. Severe infestations will cause leaves to become entirely bleached, as the mites suck the contents of the leaf cells, leaving a dead shell.

Other mites that are pests of many greenhouse crops such as tomatoes, peppers, and cucumbers include carmine mites *(Tetranychus cinnabarinus)* and broad mites *(Polyhagotarsonemus latus)*. The carmine mite is bright red in color and lacks the spots of the two-spotted spider mite. Damage to plants is similar to that of the two-spotted spider mite.

Broad mites are very small and hard to see with the naked eye. They are translucent and colorless and very small (less than 0.2 mm in length). They can be seen with a hand lens. They are fairly fast moving in the adult stage. Broad mites are particularly damaging to cucumbers and peppers. They are especially damaging to the growing tips and flower buds. They have toxic saliva that causes hardened, distorted growth of the plant tip, and symptoms look similar to a virus infection. Blossoms abort, and growing tips die and blacken, causing stunting of the plants as shown in Figure 16.69 with peppers. Fruit is badly scared and deformed in peppers and cucumbers (Figure 16.70). If broad mites are not controlled, they will eventually kill the plants.

Mites live on plant refuse and on the greenhouse framework between crops. A thorough eradication and sterilization between crops is necessary. Clear the greenhouse of all plant material and

FIGURE 16.69 Broad mite damage on pepper.

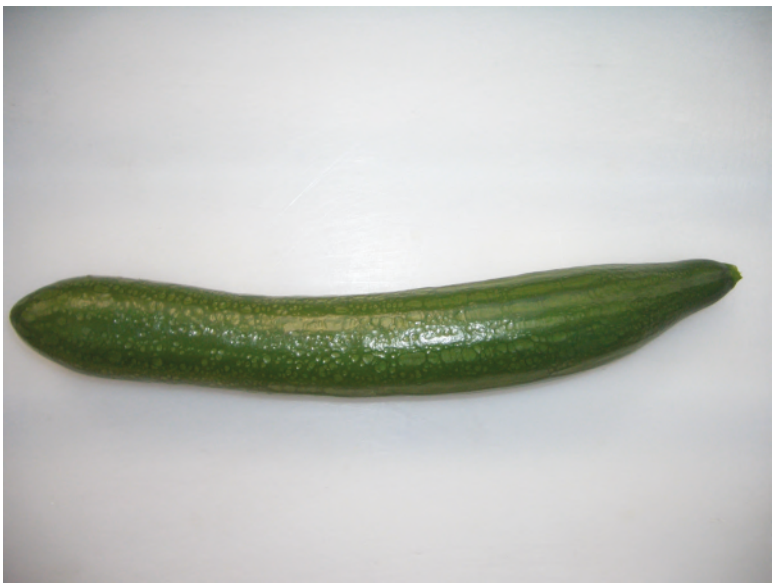

FIGURE 16.70 Cucumber fruit damaged by broad mites.

fumigate or spray with appropriate chemicals such as Verkon during power washing of the structure. If populations are very large, they will spread to most crops, including tomatoes, eggplants, lettuce, herbs, and flowers.

Control by chemical miticides must be selected to not damage beneficial insects in an IPM program. Some pesticides that can be used include Agri-Mek 0.15EC (Abamectin), Akarai, Oberon (Spiromesifen), Pycana, and M-Pede (Insecticidal Soap). While these are approved for greenhouse vegetable crops, not all are OMRI listed for organic use.

A predatory mite, *Phytoseiulus persimilis* (Spidex), is available commercially. *Phytoseiulus* differs from the two-spotted mite by its lack of spots, pear-shaped body, longer front legs, and especially its rapid movement when disturbed. In these traits it also differs from carmine mites and is much larger than broad mites. It prefers temperatures in the range of 21–27°C (70–81°F). Adults develop from eggs in less than a week. This is twice as fast as their prey. However, since bright light and high temperatures are unfavorable to their development, such hot conditions should be avoided, as these conditions also favor spider mites.

Other predatory mites are available: *Metaseiulus occidentalis*, which performs well under cooler temperatures, and *Amblyseius californicus*, which prefers warmer temperatures. A gall midge, *Feltiella acarisuga* (Spidend) *(Therodiplosis persicae)*, lays eggs in spider mite colonies. Koppert has several others: Mirical-N *(Macrolophus caliginosus)*, and Spical *(Neoseiulus californicus). Phytoseiulus macropilis* is effective in controlling carmine mites; predatory mites that effectively control broad mites include *Neoseiulus barkeri* on peppers and *Neoseiulus cucumeris* on cucumbers.

These predators are applied mainly to cucumbers and peppers, but may also be used on tomatoes, beans, gherkins, melons, grapes, strawberries, and various flower crops. Some of the predators are available in a bran substrate that can be spread on the leaves together with the predators (Figures 16.71 and 16.72).

To use *P. persimilis* or others do the following:

i. For 1 mo before introduction, do not use residual pesticides.
ii. Introduce the predator at the first sign of mite damage. If there is greater than 1 mite per leaf, reduce the population with insecticidal soap or Agri-Mek, until only 10% of the leaves are infected.

FIGURE 16.71 *Amblyseius swirskii* introduced with a bran substrate.

FIGURE 16.72 Spical (*Neoseiulus californicus*) is introduced using a shaker bottle.

iii. Maintain optimum temperatures for the predator and high RH.
iv. Generally, 8–10 predators per square meter (0.8–1.0/ft^2) should be introduced. Release in early morning onto the mid and upper foliage. Predator mites are available in shaker bottles.
v. Monitor mite population once per week.
vi. Reintroduce the predator at monthly intervals. Populations of predators should be roughly maintained at one predator for every five mites. Good control should be achieved within 4–6 wk.

3. *Aphids.* The common aphids are green peach aphid *(Myzus persicae var. persicae)*, tobacco aphid *(M. persicae var. nicotianae)*, cotton aphid *(Aphis gossypii)*, glasshouse potato aphid *(Aulacorthum solani)*, and the potato aphid *(Macrosiphum euphorbiae)*.

The life cycle varies in length from 7–10 d to 3 wk depending on temperature and season, as shown in Figure 16.73.

Aphids are usually clustered in large colonies on new succulent growth, at the base of buds, and on the underside of leaves. The most common greenhouse species is the green peach aphid. The wingless forms are yellowish green in summer and pink to red in the fall and spring. The winged forms are brown. They have a pear-shaped body 1–6 mm in length with four wings, if winged.

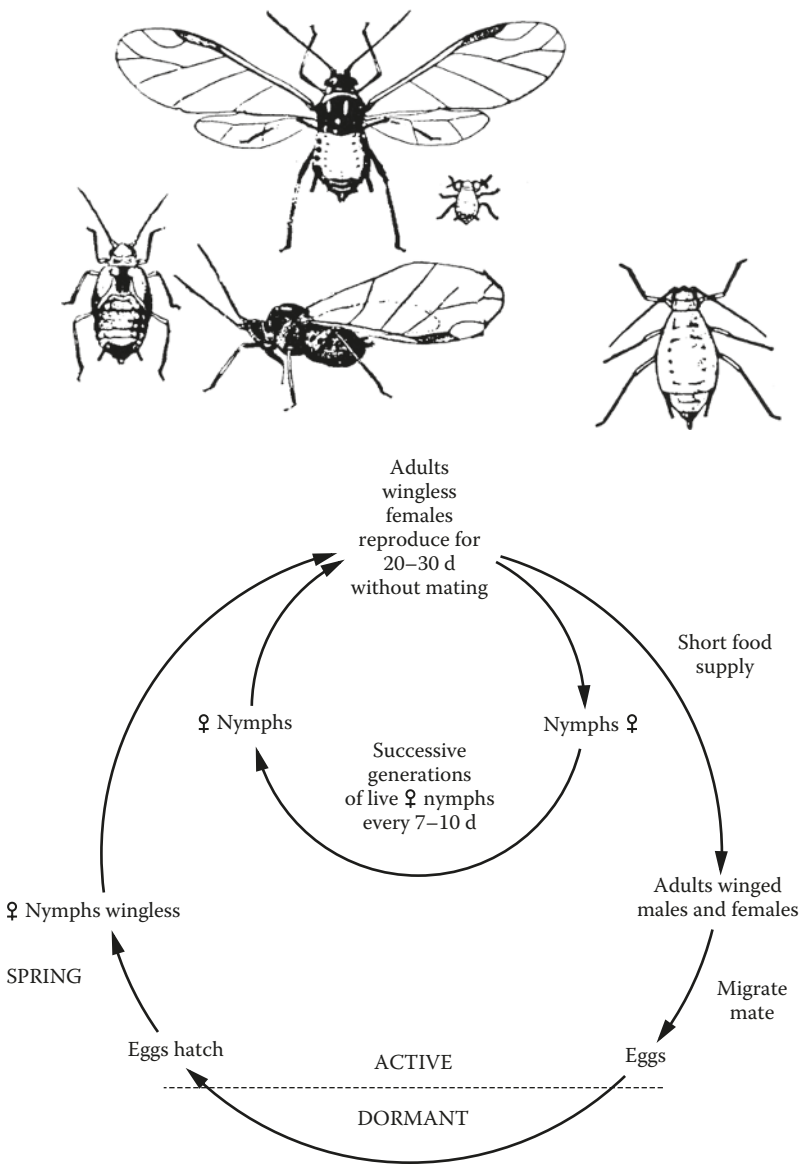

FIGURE. 16.73 Life cycle of aphid. (From J.R. Baker, North Carolina Agricultural Extension Service, Raleigh, NC. With permission.)

They excrete "honeydew" from their abdomen, which is a food for ants. The presence of large ant populations on plants often indicates aphid infestation. Aphids feed by sucking out plant sap with their tubelike, piercing mouthpart. This causes distorted leaves when they feed on young leaf buds. Under short food supply, winged females appear and migrate.

A number of types of aphids, including pink, black, and dark green, feed on most greenhouse vegetables. They suck the juices out of the plant and cause the leaves to become distorted and sticky from a honeydew deposit. Often sooty molds infect the leaves as a secondary organism, forming a black film on leaves. They also are vectors for viruses. They can be controlled with a weekly spray program using chemicals such as pyrethrin, Azatin, M-Pede, Pyganic, Fulfill, Savona (potassium salts of fatty acids), and BotaniGard.

Some biological control can be achieved using various lady beetles and the green lacewing, *Chrysopa carnea* (Chrysopa). *Aphidoletes aphidimyza* (Aphidend, marketed by Koppert) is a predaceous midge larva. The adult midge, a small, black, delicate fly lives only a few days. The female lays 100–200 eggs on the underside of leaves close to aphid colonies, which hatch in 3–4 d. A large orange or red larva, up to 3 mm long, matures in 3–5 d and drops to the ground where it forms a cocoon. Pupation takes about 10–14 d, completing a total life cycle of 3 wk.

The threshold temperature for larval development is approximately 6°C (43°F), with optimum temperatures between 23°C and 25°C (73–77°F) at 80–90% RH. Adult midges feed on aphid honeydew excretions. The larva feeds on aphids, killing from 4 to 65 aphids each.

Other Koppert products recommended for aphid control include Aphidalia (*Adalia bipunctata)*, Aphilin *(Aphelinus abdominalis)*, Aphipar *(Aphidius colemani)*, Ervibank *(Sitobion avenae)*, Evipar *(Aphidius ervi)*, and Syrphidend *(Episyrphus balteatus).*

To use *A. aphidimyza* do the following*:*

i. Control ants that may protect the aphids.
ii. Avoid using residual pesticides 1 mo before introduction.
iii. Reduce heavy aphid populations with Enstar (insect growth regulator) or insecticidal soap. Areas of at least 10 aphids per plant or one aphid per square centimeter should be left to encourage egg laying by the midge.
iv. Maintain temperatures between 20°C and 27°C (68–81°F).
v. Introduce the predator at a rate of one pupa per three aphids or two to five pupae per square meter (two to five pupae per 10 ft^2) of planted area.
vi. Spread the pupae in shady areas near aphid-infested plants and repeat introductions in 7–14 d and thereafter as necessary.
vii. Monitor plants for infestation weekly.

A parasitic fungus, *Verticillium lecanii*, trade name Vertalec, is available commercially as a biological control agent of aphids.

Spot spraying in localized infestations may be done with chemical pesticides such as insecticidal soap, Enstar, and Pirimor, but avoid spraying the *Aphidoletes* larvae. Reintroduction of the predatory larvae will be necessary in areas sprayed with chemical pesticides.

4. *Leaf miners.* The common leaf miners are tomato leaf miner *(Liriomyza bryoniae),* the American serpentine leaf miner *(Liriomyza trifolii)*, the pea leaf miner *(Liriomyza huidobrensis)*, and *Liriomyza strigata.* Adult flies are yellow-black in color and about 2 mm in length. The female deposits its eggs in the leaf, causing a white puncture-protuberance. When the larvae hatch, they eat "tunnels" through the leaf between the upper and lower leaf epidermis, creating "mines." These tunnels may coalesce, resulting in large areas of damage until the entire leaf dries up. The maturing larva drops from the leaves to the ground where it pupates. Within 10 d the adult emerges, the whole cycle from egg to adult fly takes 3 to 5 wk, as shown in Figure 16.74.

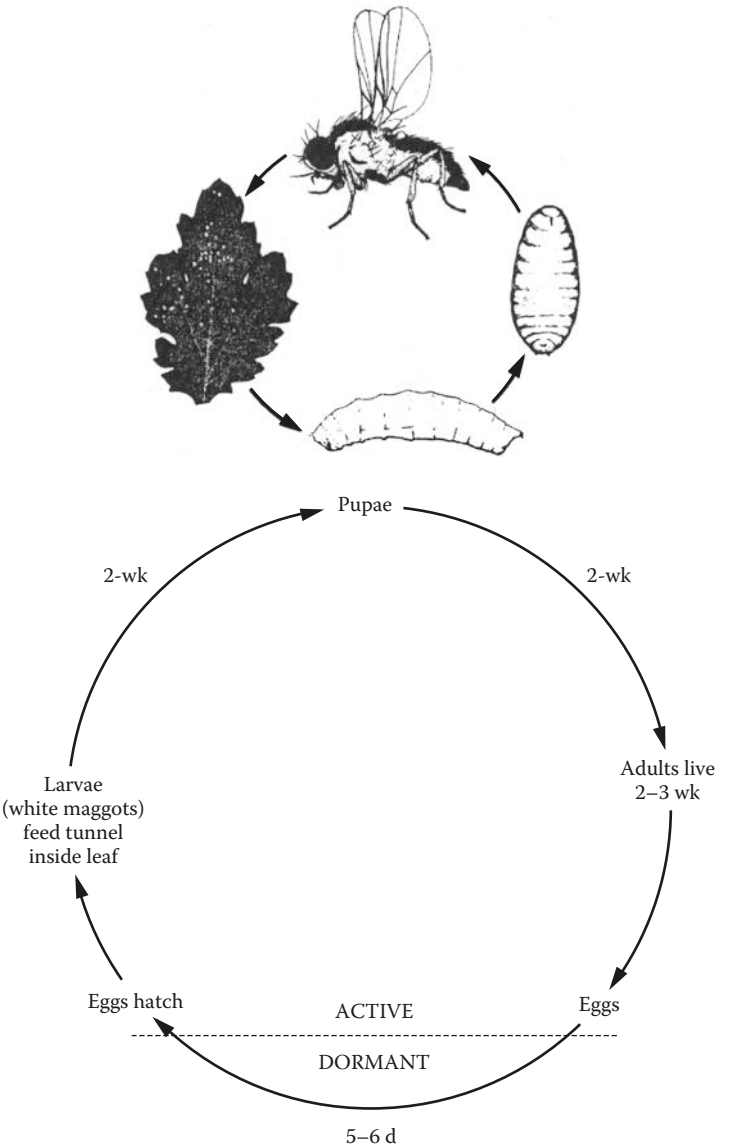

FIGURE 16.74 Life cycle of leaf miner. (From J.R. Baker, North Carolina Agricultural Extension Service, Raleigh, NC. With permission.)

Leaf miners may be controlled chemically with products such as Azatin, Entrust, Distance, and Abamectin 0.15EC (Agri-Mek). These pesticides can be used with an IPM program. There are presently several biological control agents available to control leaf miners. Some products by Koppert include Diminex (*Diglyphus isaea* + *Dacnusa sibirica)* and Miglyphus *(D. isaea).* The two insects, *D. sibirica* and *D. isaea*, parasitize both leaf miner species *L. bryoniae* and *L. trifolii.* A third, *Opius pallipes,* only parasitizes the tomato leaf miner. *Opius* and *Dacnusa* lay eggs in the leaf miner larva. As the leaf miner larva pupates, the parasite emerges instead of the leaf miner. *D. isaea* kills the leaf miner in its tunnel and lays an egg beside it. The wasp (parasite) develops in the tunnel, feeding on the dead larva.

Leaf samples must be taken from the crop and examined in a laboratory to identify the species of leaf miner, parasites present, and level of parasitism. If there are insufficient natural parasites present, *Dacnusa* or *Diglyphus* is introduced. The introduction depends on the season, the species of leaf miner, and the level of infestation.

5. *Thrips. (Heliothrips haemorrhoidalis),* onion thrips (*Thrips tabaci),* and flower thrips *(Frankliniella tritici* and *Frankliniella occidentalis).* Thrips are especially attracted to flowers of cucumbers, tomatoes, and peppers. They are particularly attracted to yellow flowers. Adult thrips are 0.75 mm long with feathery wings. They develop outside the greenhouse on weeds and invade the greenhouse. Feeding on leaf undersides, growing tips, and flowers, they cause small bleached dead spots on leaves and damage growing tips and flowers. Nymphs with rasping mouth parts scrape the leaf surface and suck the plant sap, causing a white, silvery, discoloration, resulting in streaks. Thrips feed like spider mites by puncturing and sucking the leaf contents. Damage appears as narrow crevices and a silvery appearance on leaves. They feed in narrow crevices between the calyx and the newly forming fruit of the cucumbers, causing curled and distorted fruits. Thrips similarly damage peppers. Thrips also transmit viruses such as the tomato spotted wilt virus (TSWV).

Their 2- to 3-wk life cycle begins with the adult female depositing eggs under the leaf surface (Figure 16.75). After 4 d, they hatch into nymphs that feed on the leaves for 3 d before molting into larger, more active nymphs that feed for another 3 d before dropping to the ground to pupate, and emerge as adults within 2 d. They feed for about 6 d before beginning to lay from 50 to 100 eggs over 40 d.

Yellow or blue sticky traps should be used for early detection and monitoring of the pest population. There are a number of pesticides that may be used with an IPM program. Agri-Mek 0.15EC (Abamectin), Entrust, and BotaniGard can assist in their control.

A number of biological agents are recommended to control thrips. *Amblyseius cucumeris*, a predatory mite, controls thrips. The predatory mite is similar in appearance to *Phytoseiulus*, differing only in its lighter pale-pink color and shorter legs. Its life cycle is similar to that of *Phytoseiulus.* The predator mite must be introduced in the crop at an early stage for preventive action so that a large population can be built up in order to control the thrips as soon as they appear. Their introduction and management is similar to that of *Phytoseiulus.* They should be introduced on a weekly basis until population levels reach 100 per plant. *Orius tristicolour*, a pirate bug, controls thrips in peppers and cucumbers. This predator will also feed on pollen, aphids, whitefly, and spider mites when thrip populations are low. *Hypoaspis miles* feeds on thrips' pupae. It is suitable for cucumbers, tomatoes, and peppers.

Other biological control agents available from Koppert include Entomite-A *(Hypoaspis aculeifer)*, Entomite-M *(H. miles)*, Entonem – a parasitic nematode *(Steinernema feltiae)*, Macro-Mite *(Macrocheles robustulus)*, Mycotal *(V. lecanii-m)*, Swirski-Mite *(A. swirskii)*, Thripex *(N. cucumeris)*, and Thripor-I *(Orius insidiosus)*.

6. *Caterpillars and cutworms.* Caterpillars are larvae of butterflies, and cutworms are larvae of moths. These are common in most greenhouse crops. The most important ones found in greenhouses include the tomato looper *(Chrysodeixis chalcites)*, the tomato moth *(Lacanobia oleracea)*, the cabbage moth *(Mamestra brassicae)*, the beet armyworm *(Spodoptera exigua)*, and the silvery moth *(Autographa gamma)*.

The larvae feed on aerial plant parts. Their presence is indicated by notches in leaves and cut stems and petioles. Cutworms climb up the plant and feed on the foliage at night and are found in the soil or medium during the day. Caterpillars are not nocturnal like cutworms but feed on above-ground plant parts day and night. Their presence is detected by large amounts of excrements on leaves near where they have been feeding.

Adult moths and butterflies fly into the greenhouse from outdoors and quickly lay eggs on the plants, where they hatch into feeding larvae within several days during high temperatures. Entry of

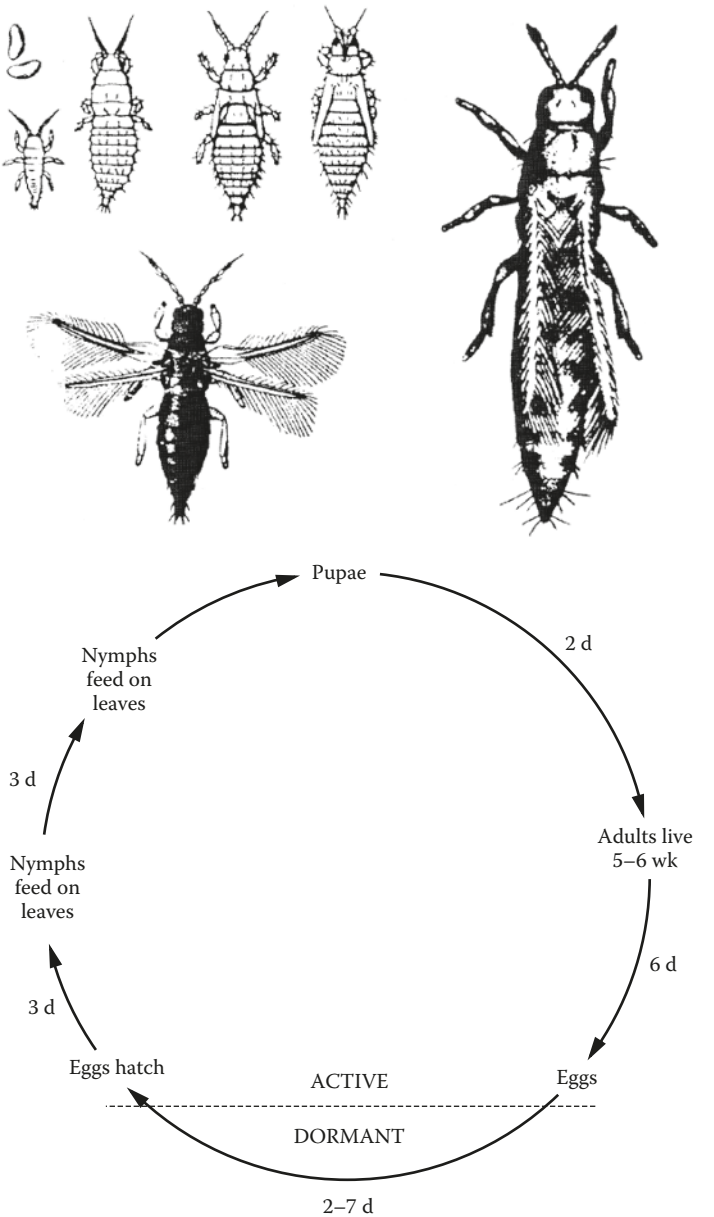

FIGURE 16.75 Life cycle of thrips. (From J.R. Baker, North Carolina Agricultural Extension Service, Raleigh, NC. With permission.)

adults should be prevented by using insect screens over shutters, vents, and so on. The time of their life cycle varies with season, temperature, and the species (Figure 16.76).

Control may be achieved by the use of a number of effective chemical pesticides such as Azatin, Pyganic, Entrust, and Malathion, as well as biological control with parasitic bacterium, *Bacillus thuringiensis*, marketed as Dipel or XenTari. This bacterium must be sprayed on a regular weekly basis, as new growth occurs to protect all surfaces. It is active only upon ingestion by the caterpillar or cutworm. The larvae are paralyzed, so they stop eating a few hours after spraying. They die within

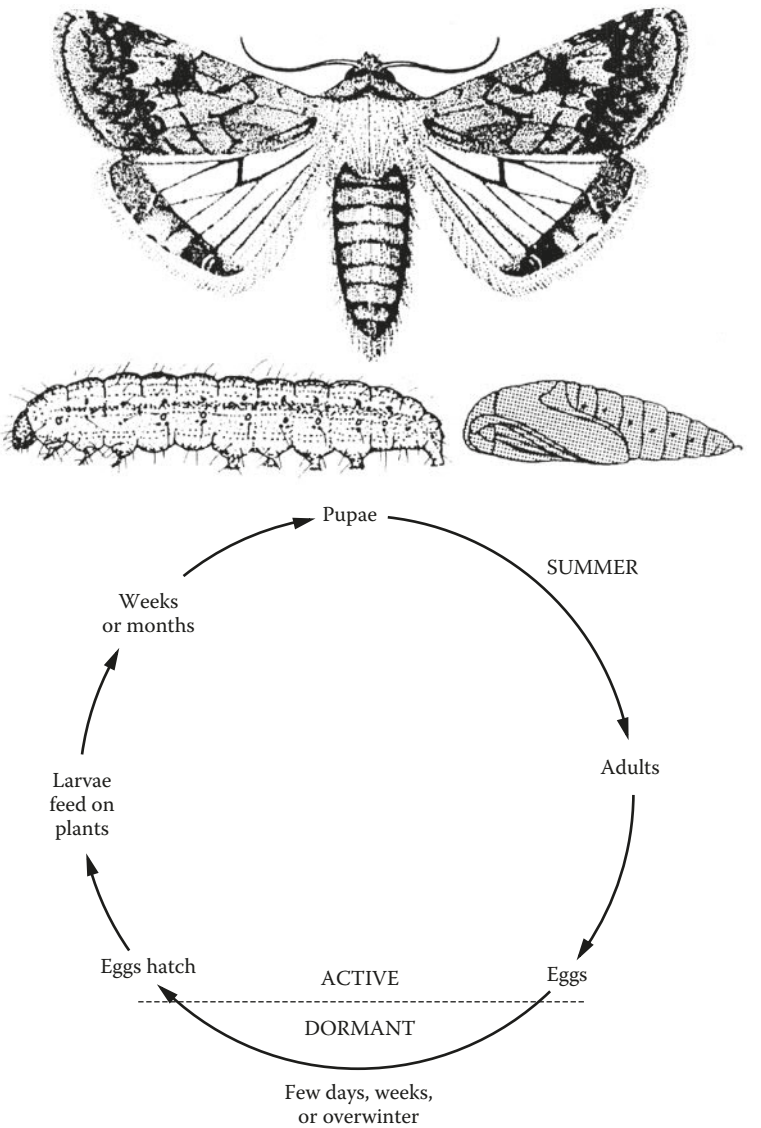

FIGURE 16.76 Life cycle of caterpillars and cutworms. (From J.R. Baker, North Carolina Agricultural Extension Service, Raleigh, NC. With permission.)

1–5 d. The bacterium is harmless to mammals, fishes, birds, and leaves no toxic residue in the environment. *Trichogramma evanescens*, a small wasp, effectively controls over 200 species of larvae by laying its eggs in the eggs of the butterflies and moths.

Other biological control agents available from Koppert include Capsanem *(Steinernema carpocapsae)*, a nematode; Entomite-A *(H. aculeifer)*; Entomite-M *(H. miles)*; and Mirical *(M. caliginosus)*.

7. *Fungus gnats (Bradysia species and Sciara species*). The larvae of these small, dark grey or black flies feed normally on soil fungi and decaying organic matter, but as populations increase, they attack plant roots. They are legless white worms about 6 mm (0.25 in.) in length with a black head. Adults have long legs and antennae, about 3 mm long, with one pair of clear wings. They attack all

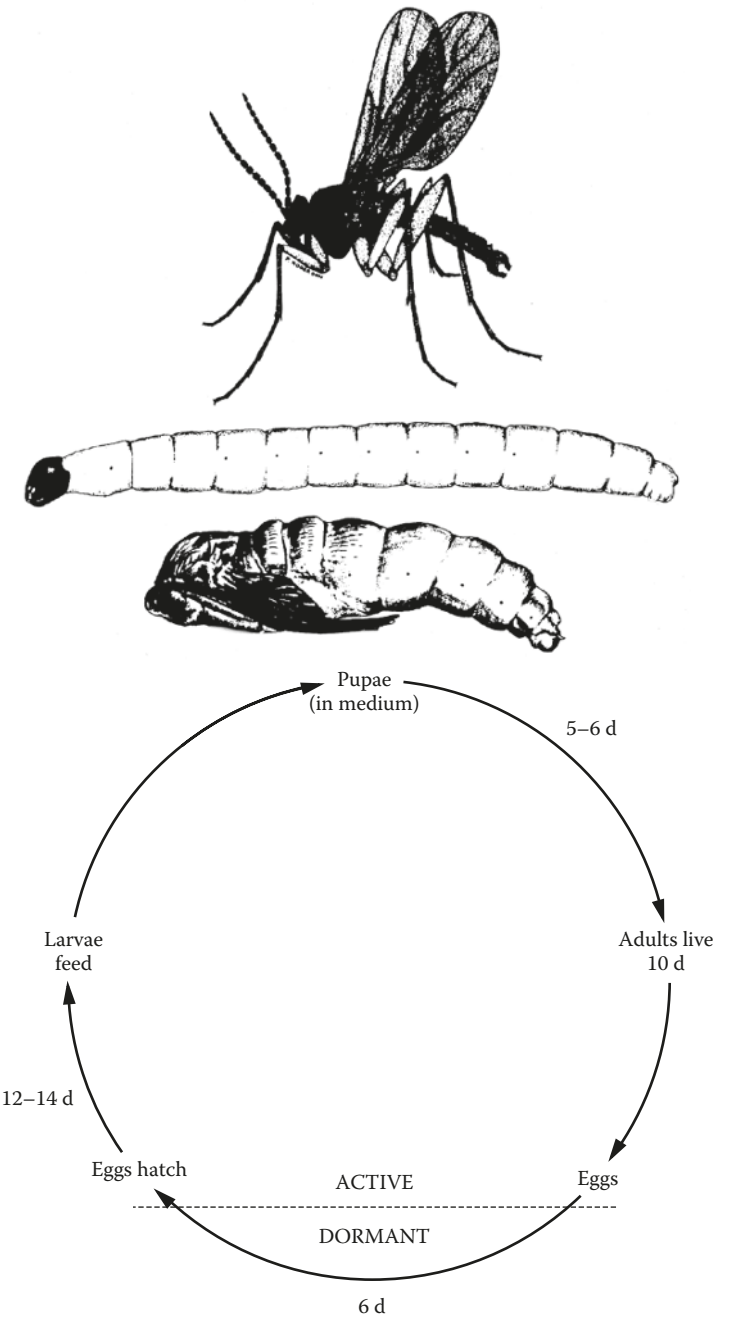

FIGURE 16.77 Life cycle of fungus gnat. (From J.R. Baker, North Carolina Agricultural Extension Service, Raleigh, NC. With permission.)

seedlings and are favored by the presence of moisture such as exists with capillary mats, seedling cubes, and the growth of algae. They also feed on the tap roots, stem cortex, and root hairs of mature cucumbers. They have a 4-wk life cycle as shown in Figure 16.77. The adults can also transmit mites, nematodes, viruses, and fungal spores. Where larvae chew the roots a port of entry is created for fungal spores to enter the plant.

FIGURE 16.78 Mealybugs on pepper leaf. Note: The adults and the protective waxy material around the colony.

Control by use of yellow sticky traps and chemical pesticides such as Diazinon are effective. Also, avoid moist areas in the greenhouse; keep medium surfaces dry. Some success has been achieved using a predatory mite that feeds on the eggs and pupae in the soil. The predatory mite, *H. miles* or Entomite-M (Koppert), feeds on fungus gnat eggs and small larvae. Entomite-A *(H. aculeifer)* is also effective. *Bacillus* bacterium may provide some control of the larvae. Vectobac, produced by Abbott Laboratories, is an effective *Bacillus* subspecies against fungus gnats. Similarly, Gnatrol, by Valent BioSciences Corporation, uses *B. thuringiensis*, subsp. *israelensis* to control fugus gnats. It must be applied weekly, similar to XenTari. An insect-parasitizing nematode, *S. carpocapsae* and *S. feltiae* (Entonem by Koppert) controls fungus gnats by entering body openings in the larvae. The nematodes are mixed with water and applied as a drench or spray or through the irrigation system.

8. *Mealybugs (Planococcus and Pseudococcus genera*). The citrus mealybug *(Planococcus citri)* is the most prevalent problem. It has been found that mealybugs are particularly troublesome in basils and peppers (Figure 16.78). They multiply rapidly and suck the sap from the plants, creating an environment favorable for secondary fungal infection by sooty molds. Mealybug infestations build quickly and cause reduced yields through deformation and yellowing of leaves, leading to leaves and flowers falling off. They excrete honeydew that favors sooty molds.

Mealybugs have five stages in their life cycle, through egg, nymphal stages (two to three), and finally adult. Females in their third larval (nymph) and thereafter develop a white waxlike substance in the form of powder, filaments, and projections, or plates that cover their bodies. This protective cover makes it very difficult to control them with pesticides, as the chemicals cannot easily contact the bodies of the mealybugs. Some chemicals used to assist in the control of mealybugs include M-Pede, Azatin, Distance, Bugitol, BotaniGard, Savona, and Enstar II. Mealybugs must be controlled early, as once established, these pesticides do not give effective control. Koppert claims that some biological control agents are available, including Citripar *(Anagyrus pseudococci)*, Cryptobug *(Cryptolaemus montrouzieri)*, Leptopar *(Leptomastix dactylopii)*, and Planopar *(Coccidoxenoides perminutus)*.

In general, life cycles of insects can be shortened under optimal temperature and RH conditions. Control of insect pests must be carried out at the most susceptible stage of their life cycle. This is usually the adult or active nymph or larval stages that are feeding. For successful integrated pest control using biological agents, the predator and prey populations must be in balance. Use of selective chemical pesticides for control of localized population outbreaks of the pest is necessary. Before using any chemical pesticides, the grower must check with manufacturers, the supplier of biological agents and/or agricultural extension personnel to determine which may be used safely. Environmental conditions within the greenhouse must be maintained at levels favorable to the predator. Weekly monitoring of predator-prey populations is needed to maintain equilibrium and new introductions of predators made to achieve successful IPM.

Natural insecticides are being introduced for use in all types of IPM programs. One such product is the active ingredient azadirachtin, an extract from the neem tree. It is marketed as Azatin or Neemix and is effective against whiteflies, aphids, thrips, leaf miners, and fungus gnats. A number of microinsecticides, produced by companies such as Emerald BioAgriculture Corporation use bread mold fungi as insecticides: *Beauveria bassiana*, *Beauveria brongniartii*, *Metarhizium anisopliae*, *Verticllium lecanii*, and *Hirsutella thompsoni. B. bassiana* is marketed under the name "BotaniGard 22WP." It is effective on whiteflies, thrips, aphids, and other soft-bodied sucking insects. Insects do not develop resistance to it, nor does it have residue problems. It does not harm *Encarsia* and in fact has an additive effect if used together to control whitefly.

The introduction of beneficial agents is a tedious task because they have to be shaken from containers onto plant leaves. Koppert has recently come out with special blowers that deliver the biological agents to the plants, saving up to 80% of the normal time to dispense them. They use airbags to apply predatory mites to the entire crop or specific areas. The blower is operated by batteries, so is very portable. With the dosage pot, the fan evenly releases the carrier material containing the natural enemies. It will carry the material up to 4 m (13 ft) from the airbag and will not harm the biological agents. Mixtures of different natural agents permit their release and uniform distribution in one step.

Hydroponic culture minimizes pests and diseases in the growing medium by efficient sterilization between crops. Pest and diseases of the aerial part of the plant, however, are not deterred by hydroponic culture. Therefore, if proper preventive programs are not followed, severe infestations may occur similar to those in regular soil-culture field conditions.

16.17 VEGETABLE VARIETIES

Many varieties of vegetables are available from seed houses. While both field and greenhouse varieties can be grown in a greenhouse, it is advantageous to use greenhouse varieties whenever possible, since they are often bred to yield very heavily under controlled environmental conditions. That is, in a greenhouse higher yields generally could be expected from greenhouse varieties than from field varieties. In most cases, greenhouse varieties cannot be easily grown under field conditions since they are unable to withstand the temperature fluctuations encountered there.

A number of greenhouse varieties of vegetables perform particularly well in hydroponic culture. These, along with other acceptable greenhouse varieties, are given in Table 16.4. The choice of variety is dependent on season, climate, and market. To initiate a project in a given area, obtain information from seed houses as to which ones should perform best under the specific conditions and then carry out trials with many to eventually find the best performers under the environment. All varieties of vine crops used in greenhouses are indeterminate or "staking" so that they may be trained vertically by strings attached to overhead support cables. These varieties have resistance and/or tolerance to many common diseases. Each variety name is followed with a code for the diseases they are resistant or tolerant to, as was explained earlier. For example, the variety Caruso with the symbol "TmC_5VF_2" indicates that it is resistant to TMV; *Cladosporium* races A, B, C, D, and E; *Verticillium*; and *Fusarium* races 1 and 2.

TABLE 16.4
Recommended Vegetable Varieties for Greenhouse and Hydroponic Culture

Vegetable		Varieties
Cucumbers:	European	*Dominica, *Marillo, *Kasja, *Camaro, *Uniflora D, Addison, Autunno, Annica, Asteroid, *Verdon, Boncanale, Discover, Davida, *Durance, DRL-9510, Eldora, *Logica, *Kalunga, Poniente, Tyria, Winmar, Cadence, Wokcue (Chinese), Bonnet, Lohengrin
Mini Cucumbers:	Beit Alpha (BA)	*Manar, Colin, Cruz, Deltastar, *Jawell, Katrina, Loon, Parakeet, Picowell, Quail, Darius, Suzan, Diva, Tornado, DPSX 419, GVS 18209, *Nimmer, Bonwell, Skywell
Lettuce:	European	*Rex, *Charles, *Deci-Minor, *Ostinata, *Cortina, *Salina, *Milou, *Vegas, Flandria, Astraca, Brighton, Elton, Laurel, Michael, Sumaya, Vincenzo, Volare, Fidel, Casey, Skyphos (red), Alexandra, Espirando, Fairly, Flandria, *Teodore (red)
	Leafy-Novelty	Multigreen1, Multigreen2, *Multigreen3, *Multired1, Multired2, Multired3, Multired4, Scanstar
	Lollo Bionda	Bergamo, Locarno, Granite, Lozano
	Lollo Rossa (red)	*Revolution, Amandine, Soltero, Azirka, Anthony
	Oak Leaf (green)	Cedar, Pagero, Torero, Veredes, *Cocarde, Kiribati
	Oak Leaf (red)	*Navara, Bughatti, Versai, Piman, *Oscarde, *Ferrari, *Aruba
	Green Leaf	Bergam's Green, *Muir, *Domineer, *Malice, Cristabel
	Red Leaf	*New Red Fire, Vulcan, *Red Sails
	Mini Romaine	Xiomara, Dragoon, Breen, Truchas (red)
	Romaine	Amadeus, Salvius, Thinker, Thumper, Intred, Monte Carlo
	Salanova Series	Butter, Batavia, Oak, Lollo, Crispy
Tomatoes:	Beefsteak	Growdena, *Trust, Beorange (orange), Frederick, *Caruso, Ducovery, *Match, *Blitz, *Quest, Heritage, Rebelski, Bigdena, *Matrix, Foronti, Tanager, Torero, Touche, Tourmaline, Rapsodie, Style, Sacher (brown), Big Sacher (brown)
	TOV	*Tradiro, *Ambiance, *Clarance, *Tricia, *Success, Endeavour, *Campari, Brillant, Lorenzo (yellow), *Orangaro (orange), Eto (brown-red), Brilliant, Speedella, Tityra, Topanga, Daniela, Komeett, Maxeza, Merlice, Extenza
	Cherry/Grape/Plum	*Favorita, *Cello, *Conchita, *Juanita, Zebra, *Goldita (yellow), Chocolate, DRC1183, DRC564, Santorange, Sweetelle, Tomagino, Garincha, Kali, Response (orange), Tomagellow (yellow), Tomarange (orange)
Tomatoes:	Cocktail	*Red Delight, Flavorino, Florino, Picolino, Goldino (yellow), Orangino (orange), Annamay, Eider, Kahlua (brown), Maitai, Tiger, *Zebrino
	Roma	*Granadero, *Naram, *Savantas, Prunus, Rimrock
	Heirloom	*Brandywine, *Striped German, Cassarosa (pink), Bocamegra (striped), 24Karat (yellow), Bucanero (brown), Pink Smart, Black Velvet (TOV), Cherokee, Red Pear, Yellow Pear
	Rootstock	*Maxifort, *Beaufort, *Estamino, *DR0141TX, Multifort, Kaiser

TABLE 16.4 (Continued)
Recommended Vegetable Varieties for Greenhouse and Hydroponic Culture

Vegetable		Varieties
Peppers (Bell Types):	Red	*Cubico, *Fantasy, *Tango, *Mazurka, *Delphin, *Ferrari, *Zamboni, 35-154RZ, Redline, Mavera, Ocelot, Triple 5, Viper, Margrethe, Maureno,
	Yellow	*Lesley, *Luteus, *Goldstar, *Samantha, *Kelvin, Bossanova, Lambourgini, Gold Flame, Crosby, Cigales, Eurix, Florate, Gialte, Sabour, Hattrick, Bachata, Baselga
	Orange	*Paramo, Sympathy, Orangery, Arancia, Boggie, *Narobi, *Fellini, Orginale, Orbit, Amber
	Green to brown	Hershey
Hot Pepper:		*Fireflame
Eggplant:	White-cylindrical (200–300 g)	*Tango
	Black/Purple-oval (350–400 g)	*Taurus, Adele, Beyonce, Jaylo, Rosheen, Fantastic, Purple, Beauty, Adagio (small 175–200 g).
	Black/Purple-half long, elongated (200–300 g)	Bartok, Black Pearl, Traviata
	Purple-white strips (350–400 g)	*Zebra, Angela
	Baby-white (175–200 g)	*Grafitti, Blanchette
	**Asian	Japanese long (dark skin): Orient Express, Chinese long (light purple): Asia Beauty, Long Purple

* Varieties particularly suitable to hydroponic culture
** For highest yields graft to tomato rootstock DR0141TX (Vineland Research and Innovation Centre, 2017).
Note: Campari can only be grown by license from the seed company.

16.17.1 Tomatoes

Older tomato varieties such as Vendor, Vantage, Tropic, and Manapel have been replaced by the Dutch varieties that are superior in vigor, yields, and disease resistance. As discussed in Chapter 10, growers are grafting the varieties onto a rootstock resistant to root rots that give higher yields. Peppers and eggplants are also grafted to these resistant rootstocks. The most popular rootstocks include, Beaufort, DR0141TX, Estamino, Maxifort, and Kaiser.

Over the past decade, cluster or tomato-on-vine (TOV) tomatoes have become very popular and now make up about 65–70% of the fresh market. The remaining 20–25% is beefsteak tomatoes and 10% is cocktail, cherry, and specialty tomatoes including romas. The market for cherry and specialty tomatoes continues to increase with less demand for beefsteak tomatoes. TOV varieties have fruit weight of 90–150 g and include varieties such as Lorenzo (yellow), Orangaro (orange), Tradiro (red), Ambiance (red), Success (red), Tricia (red), Endeavour (red), Daniela (red), and Eto (brown-red). The fruit on a cluster ripens uniformly at the same time, so the entire cluster is cut without removing the individual fruit. They are packaged in special clamshell containers to keep the fruit on the vine while sold in the market. This type of packaging also differentiates them from

conventional field-grown product. Beefsteak fruit weighs from 200 to 250 g and include varieties such as Trust, Frederick, Match, Blitz, Rebelski, Matrix, Style, and Growdena. Cherry varieties have fruit weights between 15 and 25 g. They include Favorita (red), Conchita (red), Goldita (yellow), Zebra (green stripes), Response (orange), Tomarange (orange), and Tomagellow (yellow). Specialty varieties including Picolino (red), and Flavorino (plum), Zebrino (green stripes), Goldino (yellow), Orangino (orange) and Red Delight that have fruit size from 30 to 75 g. Roma types include Naram (red), Savantas (red), and Granadero (red), with fruit weights from 100 to 150 g. These are only a few of the many varieties available from seed houses.

16.17.2 Cucumbers

It must be noted that the choice of variety is highly dependent on your specific climatic location and market acceptance. The most popular European cucumber varieties include Dominica, Marillo, Kasja, Camaro, Annica, Verdon, Durance, Davida, Logica, and Kalunga. It has been found both Marillo and Dominica are very suitable to tropical conditions under high temperatures and high prevalence of powdery mildew (PM). There are many other varieties available from the various seed producers. Some varieties are more suitable for spring/early-summer season, while others are better for summer/fall crops. They are all female, seedless varieties that set fruit without pollination. Some of the best BA varieties for tropical conditions that have most resistance to powdery mildew are Manar and Nimmer. Other popular mini cucumbers include Jawell, Darius, Diva, Picowell, Bonwell, and Skywell.

16.17.3 Peppers

Peppers are an important greenhouse crop. These are principally the sweet bell peppers, which are green, maturing to red, orange, yellow, or brown (Figure 16.79). Green-to-red varieties include Cubico, Tango, Fantasy, and Zamboni, while the green-to-yellow ones include Luteus, Samantha, Kelvin, and Lesley, especially for tropical or summer conditions. Narobi, Paramo, and Fellini are popular green-to-orange varieties. The hot red "cayenne" types are also becoming a popular

FIGURE 16.79 Greenhouse bell peppers – green, yellow, orange, and red.

greenhouse crop. One of the more productive and good flavored ones found successful in the tropics is Fireflame.

16.17.4 Eggplants

Indeterminate eggplants are available for greenhouse culture. The ones tested with great success were Tango (cylindrical, white), Taurus (oval, dark purple), and Adore (oval, dark purple). Greenhouse eggplants are becoming more common in Europe and now in North America. In 2019, there were 27 acres (11 ha) of greenhouse eggplant production with predictions of 87 acres (35 ha) by 2030. In 2019, small "baby" eggplants, such as "Graffiti" were gaining popularity in addition to white and other varieties. Greenhouse Asian eggplants include Japanese long, "Orient Express" and Chinese long, "Asia Beauty" and "Long Purple" varieties. They are trained as "high-wire" crops. They are green grafted to resistant rootstocks "DR0141TX," "Kaiser," and "Maxifort." Studies by Vineland Research and Innovation Centre in Ontario, Canada found that highest yields for Asian eggplants were achieved on "DR0141TX" rootstock (Vineland Research, 2017).

16.17.5 Lettuce

Lettuce grows very well in hydroponic culture. There are four basic types of lettuce: European or Bibb lettuce, looseleaf lettuce, head lettuce or iceberg, and cos or romaine lettuce. While many varieties of each type are available from seed houses, there are a few of each type that are particularly well suited to hydroponic culture and greenhouse environments. The most suitable varieties of European or Bibb lettuce are Deci-Minor, Ostinata, Rex, and Charles. Rex is especially resistant to "bolting" under high temperatures in tropical conditions. They should be planted at 15 cm x 20 cm (6 in. x 8 in.) spacing. Bibb lettuce requires a night temperature of 18°C (65°F), a day temperature of 17–19°C (63–66°F) on dull days and 21–24°C (70–75°F) on sunny days. They take about 45–60 d from seeding to maturity, depending on available sunlight.

Looseleaf varieties are generally the easiest to grow. Varieties such as Cristabel, Domineer, Muir, and Malice are very vigorous in hydroponic culture. They require between 45 and 50 d to mature. Their spacing and temperature requirements are similar to European lettuce. Looseleaf varieties require night temperatures of 10–13°C (50–55°F) and day temperatures of 13–21°C (55–70°F), depending on sunlight. However, they will tolerate higher temperatures up to 27°C (80°F) without wilting, bolting, or slowing growth. But if higher temperatures occur, "burning" of the leaf tip or margin may result. Some varieties are more tolerant to higher temperatures and resist "tip-burn."

Of the many head lettuce varieties available, Great Lakes 659 and Montemar grow best in hydroponics and greenhouse environments. They are most suitable to tropical conditions as mentioned in Chapter 15. They take between 80 and 85 d from seed to mature and will tolerate higher day temperatures up to 27–28°C (77–78°F) without bolting, provided they receive full sunlight. Head lettuce should be spaced slightly wider apart at 25 cm x 25 cm (10 in. x 10 in.).

Romaine (Cos) lettuces have temperature requirements similar to those of looseleaf lettuces. Mini romaine varieties such as, Dragoon, Breen, and Truchas have been grown under higher temperature conditions of the tropics and are popular in greenhouse production. Several novelty varieties that can tolerate the higher temperatures of the tropics are Red Salad Bowl, Green Salad Bowl, Cocarde, Oscarde, Ferrari, and Aruba (oakleaf types). Red Sails and New Red Fire are red looseleaf lettuces that tolerate higher temperatures. The Salanova series is also cultivated in greenhouses for the basis of many salad mixes. They are an industry standard in baby leaf production to add interesting shapes and colors to packaged salad mixes. Seed houses such as Johnny's Selected Seeds, offer seed mixes of lettuces and greens that can be harvested at 3–4 wk for use in salad mixes. They claim their mixes are balanced for color, texture, and flavor. Some of their combination mixes include Allstar Gourmet Lettuce Mix, Five Star Greenhouse Lettuce Mix, Encore Lettuce Mix, and Wildfire Lettuce

Mix. However, commercial greenhouse growers of packaged lettuce and leafy greens mixes prefer to make up their own signature brands of varying percentages of each of these components. These mixes include various baby leaf lettuces, romaine, arugula, kale, spinach, chard, bok choy, mustard greens, mizuna, and herbs. Refer to Chapter 6 for growing of baby leaf crops for salad mixes.

Lettuce should be seeded in rockwool cubes, Oasis cubes or flats of soilless medium as discussed earlier. Transplanting into growing beds should take place once the seedlings are 5–6 cm (2–2.5 in.) in height (about 20–23 d after seeding).

16.18 GREEN GRAFTING

Grafting is an important procedure in the growing of greenhouse tomatoes, peppers, and eggplants. It is particularly important in tomatoes to give more vigor and disease resistance against Corky Root, TMV, *Fusarium*, and *Verticillium* wilts, and nematodes (Black et al., 2003; Rivard and Louws, 2006). The rootstocks increase water and nutrient uptake to give more vigorous plants.

Refer to the seed houses for specific recommendations of which rootstocks to use with a particular variety. In general, use Beaufort with cherry and novelty tomatoes and Maxifort or Manfort with TOV and beefsteak varieties. Rootstocks for eggplants include Beaufort, DR0141TX, Kaiser, and Maxifort. Be aware of any growth rate differences between the rootstock and variety (scion) to determine whether the rootstock should be sown a few days before or after the scion. For example, Beaufort (rootstock) and Favorita (scion) can be sown at the same time, as they have similar growth rates. If the variety (scion) grows faster than the rootstock, seed the rootstock several days earlier than the variety and vice versa. This is important so that the rootstock and variety (scion) stems have the same thickness when they are ready to graft (approximately 17 d). This is usually when they have two to three true leaves and a stem diameter of about 2 mm.

Sow the rootstock in the final substrate cubes, such as rockwool cubes, which would later be transplanted to rockwool blocks and afterward to the growing system. The variety (scion) can be sown in compact multitrays of 72 cells with a peat-lite medium or coco coir. After grafting, these plant roots will be disposed of. If there are significant size differences among the rootstocks or scions, sort them several days prior to grafting according to the same stem thickness. Grafting should be possible about 17 d after sowing.

Cut off the rootstocks of a tray with a razor blade at a 45° angle (Figure 16.80). The rootstock should be cut off underneath the cotyledons, if possible. The stem should be at least 2–3 cm (1-in.) long at that location. Too short stems can cause the variety to form aerial roots that could later root into the substrate. This occurs if the aerial roots come into contact with moist substrate. Place silicone or spring-loaded plastic plant clips half way into the cut rootstocks. Cut off the plants of the variety (scion) at the same angle as the rootstock. Be sure that it is the same diameter as the rootstock at that location. It is easier if it is above the cotyledons. Cut off only as many tops (heads) as needed for the prepared rootstocks.

Place the scion in the clips of the prepared rootstocks being careful that they contact 100% (Figure 16.81). Air or dirt between the two parts will result in failure of the grafting. Lightly mist the plants and place them in a misting chamber. The misting chamber or tunnel must be prepared in advance of the grafting procedure. Spray or mist the inside of the tunnel to increase humidity and close it tightly to prevent drying. Be sure to shade the grafted plants in the tunnel to reduce evaporation.

Optimum temperature for grafting is 22–23°C or 72–73°F. Avoid temperatures in the tunnel above 28–30°C (82°F–86°F).

Keep the tent closed for 3 d; mist the plants lightly if they show any signs of wilting. On the fifth day open the sides of the tunnel to ventilate briefly, and on the sixth day open or roll up the sides a little. On the seventh day remove the tunnel, preferably in the morning; if wilting occurs, cover the plants again in the tunnel. By this time, the graft union should have healed, and the plants will not

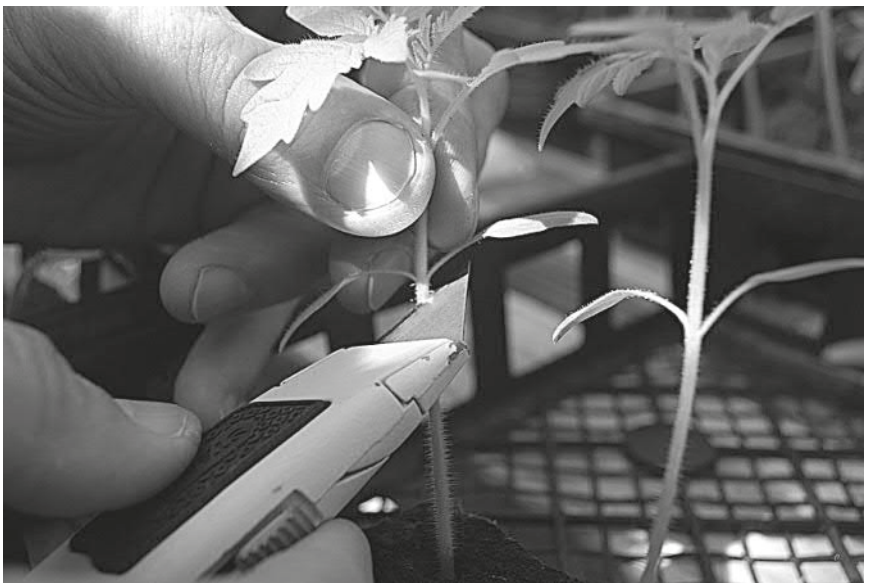

FIGURE 16.80 Cut the scion with a razor or gyproc knife at a 45° angle underneath the cotyledons.

FIGURE 16.81 Place a plant clip on the graft union.

FIGURE 16.82 Aerial roots may form above the graft union on the scion.

wilt when removed from the tunnel. Aerial roots may form above the graft union (Figure 16.82). Transplant them to the rockwool blocks several days later, at day 9 or 10. Do not lay the seedlings on their sides in the blocks, as that would cause the scion (variety) to root and defeat the grafting purpose (Figure 16.83).

After the plants have been growing for a number of months and are bearing fruit the graft union remains visible as a distinct line as shown in Figure 16.84. Grafting clips are available from seed houses. They come in several sizes; the silicone ones are available in 1.5- and 2.0-mm diameters, and the spring-loaded plastic clips are available in sizes ranging from 1.5 to 6 mm in diameter. The choice depends on what size of plant stems will be grafted. It has been found that the 2.0- to 3.0- mm clips are best for grafting tomatoes early.

16.19 PLANTING SCHEDULES

A number of planting schedules are possible depending on what crop or combination of crops is to be grown over the entire year. If only tomatoes are to be grown, a spring and fall crop system is used, as shown in Table 16.5. Particularly when growing on a backyard scale, intercropping of lettuce is recommended for the spring crop of tomatoes. This intercropping is not practical for commercial growers. Lettuce should be seeded and transplanted into the beds at the same time. One to two lettuce plants can be placed between each pair of tomato plants. The tomatoes will soon grow above the lettuce, so they will not be shaded by them. While the tomatoes are still small, 12–18 in. (30–45 cm) in height, the lettuce will receive sufficient light to produce well. In this way, a crop of lettuce can be harvested at least 1 mo before the tomatoes will be ready. After this initial intercropping of lettuce, further intercrops can be place under the tomatoes once the tomatoes are fully

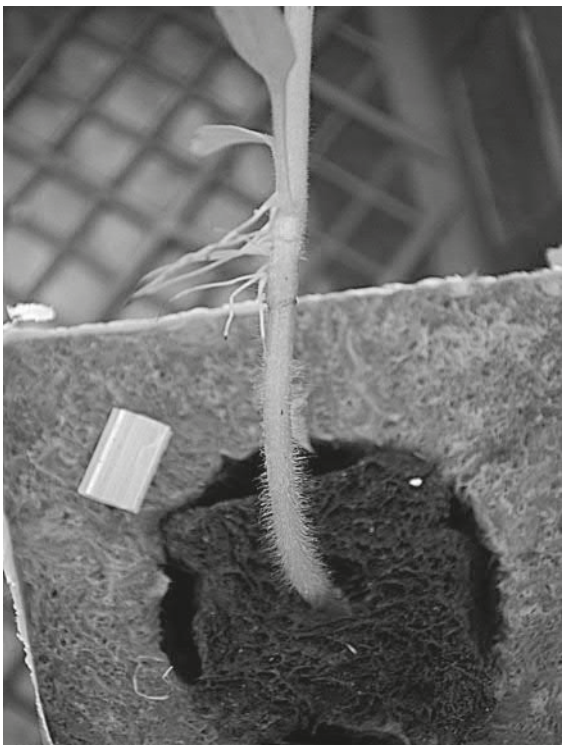

FIGURE 16.83 Place seedling upright in block. Note: The graft union below the aerial roots.

FIGURE 16.84 Graft union remains visible throughout the growth of the plant.

TABLE 16.5
Planting Schedule for a Spring and Fall Crop of Tomatoes (Two Crops Annually) (Backyard Greenhouses Only)

Date	Activity
Dec. 20–31	Sow lettuce and tomato seeds in rockwool cubes
Jan. 21	Transplant lettuce seedlings into hydroponic system
Feb. 1–15	Transplant tomato seedlings into hydroponic system
March 1	Harvest lettuce
April 1–15	Begin harvesting tomatoes
May 15	Sow lettuce
June 1–15	Sow tomato seeds in cubes for the fall crop; terminate tomatoes; transplant lettuce intercrop under existing tomatoes
July 1	Harvest lettuce, pull tomato plants of spring crop, clean greenhouse, sterilize, and so on.
July 15	Transplant fall tomato crop and lettuce intercrop into hydroponic system.
Aug. 15–31	Harvest lettuce
Sept. 15	Begin harvesting tomatoes
Dec. 20–31	Pull plants of fall crop, clean up, sterilize, and so on, sow lettuce and tomato seeds of spring crop

mature and several trusses of fruit and all the leaves up to the maturing truss have been removed. This will be about May, as shown in Table 16.5. One intercrop of lettuce could be grown with the fall crop through July and August (Table 16.5).

Intercropping on a commercial scale has already been discussed in Chapter 10. This type of intercropping applies to tomato crops when an older crop is being replaced by younger plants that have been transplanted among the existing mature crop. Other forms of intercropping with different crops are not common practice in commercial greenhouses due to different nutrient and environmental needs of the different crops.

Cucumbers grown year-round may be scheduled in numerous ways. Some growers prefer to grow three to five crops a year, especially under semitropical or tropical conditions (Table 16.6). Others grow only one long crop from December through mid-November using the renewal umbrella system (Table 16.7). Most growers now use a two- to three-crop schedule.

Peppers are now a common greenhouse crop grown as a single crop annually from October through November as shown in Table 16.7.

Eggplants are grown on the same crop schedule as cucumbers as two or three crops per year depending on the location. A three-crop schedule is preferable, as they are difficult to lower and suffer a lot of stress during such a procedure, as was described earlier in this chapter.

16.20 CROP TERMINATION

In the growing of tomatoes, the growing point of each plant should be cut off 30 d before the expected date for pulling of the plants (Table 16.5). During this 30-d period, remove the many suckers which will develop at the top of the plants.

Several days before starting the clean-up, spray the plants to kill any insect infestations. Be careful not to use any pesticides having long-term residual effect, which may harm the beneficial predators of the IPM program of subsequent crops. Stop the flow of water and nutrients to the slabs or beds a few days before physically removing the plants from the greenhouse. Pull out the roots, or cut the base of the stems, but leave the rest of the plant still supported by the string and some clamps. It is easier to remove most of the plant clips before cutting the plants if the clips are to be recycled,

TABLE 16.6
Three-Crop Schedule for Annual Cucumber and Eggplant Production

Date	Activity
Jan. 1	Sow cucumber seeds
Feb. 7	Transplant into growing system (first crop)
March 7	Begin harvesting cucumbers
April 21	Sow cucumber seeds (second crop)
May 15	Pull cucumbers of first crop, clean up, and so on
May 21	Transplant cucumbers into growing system (second crop)
June 21	Begin harvesting cucumbers (second crop)
Aug. 15	Sow cucumber seeds (third crop)
Aug. 31	Pull cucumber plants of second crop, clean up, and so on
Sept. 15	Transplant cucumbers into growing system (third crop)
Oct. 15	Begin harvesting cucumbers (third crop)
Dec. 20–31	Pull cucumbers of third crop, clean up, and so on

TABLE 16.7
Single Crop of Tomatoes, Cucumbers, or Peppers

Date	Activity
	Tomatoes
Nov. 7–14	Sow tomato seeds
Nov. 30	Transplant to larger rockwool blocks under supplementary lighting with a DLI of 13 -16 mol/m^2/d as discussed in section 16.3.1.
Dec. 14	Set plants in rockwool blocks on top of slabs in greenhouse
Jan. 1–7	Transplant tomatoes into slabs (beds) when flower buds appear
Feb. 15–21	First harvest
Nov. 21	Last harvest
Nov. 21–Dec. 7	Remove plants, clean up, and so on
	Cucumbers
Dec. 1	Sow cucumber seeds in seedling house
Jan. 1–7	Transplant to slabs or beds in greenhouse
Feb. 1–7	Begin harvesting cucumbers
Nov. 15	Last harvest
Nov. 15–Dec. 15	Remove plants, clean up, and so on
	Peppers
Oct. 1	Sow pepper seeds in seedling house
Oct. 21	Transplant peppers to rockwool blocks in seedling greenhouse
Nov. 21	Transplant to slabs or beds in greenhouse
Feb. 7–15	Begin harvesting peppers
Nov. 15–21	Last harvest, remove plants, clean up, and so on

Note: See Chapter 10 for more details on cropping procedures.

otherwise dispose of them with the plants. The plant clips can be reused after soaking and washing them in a bleach solution. By cutting the stems, the plants will lose a lot of water and thus reduce the overall plant weight to be removed from the greenhouse. Dispose of the plants in the garbage or on a compost pile or bury them some distance from the greenhouse to avoid any disease or insect reinfestation of the new crop. After all of the plants have been removed from the greenhouse, sweep or vacuum all the floors clean, so that no plant debris remains. The beds, nutrient tanks, and growing medium must be thoroughly sterilized according to measures given in earlier chapters.

Flush irrigation lines with nitric acid at a *p*H of 1.6–1.7 (60–70% concentrate diluted 1 part acid to 50 parts water) for 24 h. Make this up in the blending tank and run each station for 2 minutes to allow the acid solution to thoroughly flush through the system. Let the lines sit full of the acid solution for 24 hours. Rinse the lines after 24 h with fresh water and check the *p*H of the drain water to determine that it is above 5.0 before flushing the lines with a 10% bleach solution. Be careful that the *p*H is not low because of the presence of acid; if there is any acid remaining it will react with the bleach solution to produce toxic chlorine gas. Flush the lines four times for 2 min each every hour over a 4-h period. Leave the final flush in the lines for 24 h. After that, rinse the lines with fresh water.

Power wash the walls, roof, and floor with a sterilant such as Virkon, followed with a 10% bleach solution. Virkon is applied at a rate of 1.0% solution. As Virkon is a powder, mix 1 kg (2.2 lb) per 100 L (26.4 US gal) of water. Once everything has been completely sterilized, the system is ready for its next crop.

A hydroponic system, if properly sterilized and cleaned between each crop, will continuously yield heavy crops over the years, giving its operator higher returns than could be achieved over the long term with soil.

16.21 SPECIAL CONSIDERATIONS

Whether plants are grown hydroponically or in soil, their cultural requirements are the same. Specific information on the growing of various plants is available from gardening books and various extension bulletins issued by universities and agricultural departments. A list of some university extension offices is given in Appendix 2.

Commercial greenhouses are now closely scrutinized by various environmental groups. As a result, use of water, runoff, pesticides, and fertilizer wastes are important aspects to be controlled. Greenhouses are being forced to reuse water, minimize the use of pesticides and fertilizers, and recycle wastes. Recycling of plant materials could be achieved through their use in animal foods. Water and fertilizer usage can be minimized with recirculation hydroponic systems of rockwool, coco coir, and NFT cultures. Pesticide use is largely reduced by employing biological agents in an IPM program. The use of fungicides is being reduced through biological controls and the breeding of disease-resistant varieties. Research in more efficient hydroponic methods, nutrient analyses, and automatic solution adjustment with sterilization of the solution during each passage through the nutrient solution reservoir, all monitored and controlled by a central computer, are some of the present practices in hydroponic culture.

Sustainable cropping systems are now the buzz word in agriculture, and particularly in greenhouse hydroponics. As was discussed in Chapter 11, coco coir substrate is the basis for such sustainable agriculture. Greenhouse structures and hydroponic systems that recirculate and adjust their environment and solutions are part of this program. Recently, the use of solar panels in the generation of electricity for the greenhouse is the next step. In 2011 a German company constructing 5 ha (12.5 acres) of high-tech greenhouses using new solar panels that are mounted on the roof to provide electricity and shading for the greenhouse. A California-based company, Solyndra, has developed this solar panel, which doubles to provide shade through diffusion of light and to generate electricity. They are working with the Regional Center of Experimentation and Agricultural Assistance

in Milan, Italy, and the Department of Plant Sciences at the University of California Davis (www.coolerplanet.com).

An article in www.freshplaza.com on May 10, 2011 reported that the company Micothon, which invented an air-assisted spraying technique that gives better penetration and coverage in applying pesticides than conventional spraying systems, is working with Clean Light BV in developing a "Clean Light UV Crop Protection" system for disease management (www.micothon.com and www.cleanlight.nl). Combined with their "Micothon Spraying Robot," it reduces the use of chemicals in greenhouses and helps to protect against fungi, bacteria, and viruses. Micothon claims with their air-assisted spraying technology one can realize up to 79% better spraying results compared to standard spraying equipment. This gives optimal protection of the crops, with a large reduction in use of pesticides and reduced labor costs from its automated operation. The tube/rail sprayer automatically drives on the heating rail pipes according to the set program of the machine and sprays the entire greenhouse without an operator.

Automation with robotics is advancing very rapidly in performing daily tasks in greenhouses and vertical indoor farms. Labor is a significant operational cost in greenhouses and the shortage of available farm workers is limiting production by not completing daily tasks. Robots have been developed for harvesting crops in the greenhouse as discussed in Chapter 12. Many automated NFT systems of growing leafy greens, lettuce, and herbs are leading the growing methods for low-profile crops. These systems were discussed in Chapters 5 and 6. Automation using sensors for climate control, irrigation, nutrition, CO_2 enrichment, and plant health, monitor and feedback to central computer systems to control growing parameters. AI and robotics is the way of future greenhouse culture.

LED grow lights now provide adequate light over large areas to enable their use in commercial greenhouse operations. They are more efficient in converting energy to light than the present HID lights. This lighting in the future may provide an opportunity to construct vertical greenhouses in cities. Refer to Chapter 12 on the types of LED lighting for greenhouses.

This effective control provides hydroponics with the potential of becoming the solution to intensive crop production throughout the world, and in man's future travels to other planets. Hydroponic experiments are now being conducted by several companies sponsored by NASA in its space program. It is to be the method of providing fresh vegetables to astronauts on the space station and future space travel. Experiments on the growing of plants in space are now scheduled for space flights in the near future. Hydroponic systems have been designed and tested to operate under microgravity environmental conditions of spaceflight. A biomass chamber has been designed for NASA's "Controlled Ecological Life Support System" (CELSS). Many studies are currently underway to develop equipment and cultural procedures to grow crops hydroponically in space. With increasing interest in establishing colonies on Mars, hydroponic culture is to play a key role in growing food for the astronauts there.

Hydroponics is a universal science in that it can be applied to very simple systems such as individual pots of soilless substrate in homes or inexpensive units constructed by individuals themselves in searching for methods of growing basic food crops. This often occurs in poor neighborhoods of countries like Peru, Colombia, Venezuela, and so on, where people may not have the financial ability to buy nutritious vegetables in the marketplace. It is key part of the worldwide greenhouse vegetable and ornamental plant industry. It is used in isolated environments like the McMurdo Research Station in Antarctica to grow vegetables in a closed environment.

Hydroponics is now being incorporated into cities through rooftop hydroponic greenhouse operations as was discussed in Chapter 15. Indoor vertical farms (VFs), as discussed in Chapter 14, are the greatest expansion of hydroponic growing systems developed in the past few years with hundreds of millions of dollars of investment, often public funds. With LED lighting and automation systems the VFs are dominating new growing facilities worldwide. The advantages of VFs are their ability to be located in any climate and very near or within large cities. However, only a few

are profitable because of the high capital and operational costs especially that of electricity for the lighting. Nonetheless, as techniques and automation become a larger part of the operations, costs will be lowered resulting in potential profits. Since VFs are located in air-conditioned buildings it makes the growing of crops possible under any ambient weather conditions since temperatures, RH, and CO_2 can be precisely controlled. Transportation costs to markets are greatly reduced by locating the VFs within cities. At present VFs are attracting a lot of publicity and investment as they are viewed as the way of the future for many agricultural crops, but at this time, are only feasible for low-profile crops such as lettuces, leafy greens, salad mixes, and herbs.

This universal science of hydroponics will continue to enter into new applications in providing highly nutritious vegetables for us under all environmental conditions.

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Appendix 1
Horticultural, Hydroponic, and Soilless-Culture Societies

The largest organization that participates with conferences and symposiums internationally and publishes scientific papers on horticulture is the International Society for Horticultural Science (ISHS) (www.ishs.org). They participate with many hydroponic societies in organizing events on hydroponic culture and horticulture.

Anyone who is interested in any aspects of horticulture, including hydroponics may apply for membership in the ISHS. ISHS membership gives you access to publications, symposia, mailing lists, and online services to develop information networks with colleagues having similar interests and concerns in resolving solutions to your challenges. This knowledge is shared on an international scale. The ISHS has online forms to apply for membership.

Other hydroponic societies in the world include:

The Australian Hydroponic and Greenhouse Association (AHGA) (renamed Protected Cropping Australia) (PCA). The website is: www.protectedcroppingaustralia.net.au.

In Brazil, the Encontro Brasileiro de Hidroponia (www.encontrohidroponia.com.br).

Asociacion Hidroponica Mexicana A.C., Mexico (www.hidroponia.org.mx).

Hydroponic culture technology is very active in Peru at Universidad Nacional Agraria La Molina, Lima, Peru. In 1994, the Centro de Investigacion de Hidroponia y Nutricion Mineral (CIHNM) at the Universidad Nacional Agraria La Molina (UNALM) was established. It continues providing courses and conferences recognized both nationally and internationally. Their website is www.lamolina.edu.pe/hidroponia.

The Singapore Society for Soilless Culture (SSSC): 461 Crawford Lane #13–75, Singapore 190461.

Others may be found by searching on Google under "Hydroponic Societies" or "Hydroponic Associations." There are also many forums that one can join to participate in discussions and problem solving with other members.

Taylor & Francis
Taylor & Francis Group
http://taylorandfrancis.com

Appendix 2
Greenhouse Production Resources

RESEARCH EXTENSION SERVICES FOR PUBLICATIONS

Presented here are a few typical sources of information for horticulture, including hydroponics. Nonetheless, the best way to search for information is with specific requests through search engines, such as Google, on the Internet.

Superintendent of Documents: U.S. Government Printing Office: www.gpoaccess.gov, www.gpo.gov, www.bookstore.gpo.gov, www.access.gpo.gov.
Wikipedia Cooperative Extension Service: http://en.widipedia.org/wiki/Cooperative_extesnion_service
Alabama Cooperative Extension System: www.aces.edu/
Arizona Cooperative Extension: http://extension.arizona.edu/
University of California Cooperative Extension: http://ucanr.org/
University of Connecticut Extension Services: www.extension.uconn.edu/
University of Florida IFAS Extension: http://solutionsforyourlife.ufl.edu/
University of Georgia Cooperative Extension: http://ugaextension.com/
University of Illinois Extension: www.extension.uiuc.edu/
Purdue University Extension: www.ces.purdue.edu/
University of Kentucky Cooperative Extension Service: www.ca.uky.edu/ces/index.htm
Michigan State University Extension: www.msue.msu.edu/
Minnesota Extension Service: www.extension.umn.edu/
Mississippi State University Extension: (http:/msucares.com
Rutgers Cooperative Extension: www.rce.rutgers.edu/
Cornell Cooperative Extension: www.cce.cornell.edu/
North Carolina Cooperative Extension Service: www.ces.ncsu.edu/
The Ohio State University Extension: http://extension.osu.edu/
Oregon State University Extension Service: http://extension.oregonstate.edu/
Penn State Cooperative Extension: www.extension.psu.edu/
Texas A & M University-Texas AgriLife Extension Service: http://texasextension.tamu.edu/
Utah State University Extension: www.ext.usu.edu/
Washington State University Extension: http://ext.wsu.edu/
University of Wisconsin Extension: www.uwex.edu/ces/

SOME SOIL AND PLANT-TISSUE TESTING LABORATORIES

A&L Southern Agricultural Laboratories, Pampano Beach, FL
A&L Canada Laboratories East, Inc., London, Ontario: www.alcanada.com
A&L Eastern Laboratories, Inc., Richmond, VA: http://al-labs-eastern.com
A&L Great Lakes Laboratories, Inc., Ft. Wayne, IN: www.algreatlakes.com
A&L Plains Laboratories, Inc., Lubbock, TX: www.al-labs-plains.com
Albion Laboratories, Inc., Clearfield, UT: www.AlbionMinerals.com

ALS Laboratory Group, Saskatoon, SK: www.alsglobal.com
Agrichem Analytical, Saltspring Island, BC: www.agrichem.ca
Agsource Harris Laboratories, Lincoln, NE: http://harris.agsource.com
Analytica Enviornmental Laboratories, Inc., Thornton, CO: www.analyticagroup.com
Brookside Analytical Laboratories, New Knoxville, OH: www.blinc.com
Colorado Analytical Laboratory, Brighton, CO: www.coloradolab.com
Colorado State Soil, Water and Plant Testing Laboratory, Fort Collins, CO: www.extsoilcrop.colostate.edu/SoilLab/soillab.html
Cornell University Analysis Laboratory, Ithaca, NY: http://cnal.cals.cornell.edu/analyses/index.html
Energy Laboratories, Inc., Casper, WY: www.energylab.com
Enviro-Test Laboratories, University of Saskatchewan, Saskatoon, SK: www.envirotest.com
Exova, Surrey, BC: www.exova.com
Hill Laboratories, Hamilton, New Zealand: www.hill-laboratories.com
Kansas State Research and Extension Soil Testing Laboratory, Manhattan, KS: www.agronomy.ksu.edu/soiltesting/
Kinsey's Agricultural Services, Charleston, MO: www.kinseyag.com
Les Laboratoires A&L du Canada, Saint Charles sur Richelieu, Quebec: www.al-labs-can.com/soil/ser_QCsoil.html
Maxxam Analytics, Burnaby, BC: www.maxxam.ca
MB Laboratories Ltd., Sidney, BC: www.mblabs.com
Micro Macro International, Inc., Athens, GA: www.mmilabs.com
Midwest Laboratories, Inc., Omaha, NE: www.midwestlabs.com
Midwestern Bio-Ag, Blue Mounds, WI: www.midwesternbioag.com
Northwest Labs, Edmonton, AB and Winnipeg, Manitoba: www.norwestlabs.com
Olsen's Agricultural Laboratory, Inc., McCook, NE: www.olsenlab.com
Servi-Tech Laboratories, Dodge City, KS: www.servitechlabs.com
Scotts Testing Lab, Allentown, PA: www.scottsprotestlab.com/plantTesting.php
Soil and Nutrient Laboratory, University of Guelph, Guelph, ON: www.uoguelph.ca/labserv
Soil and Plant Analysis Laboratory, University of Wisconsin, Verona, WI: http://uwlab.soils.wisc.edu
Soil & Plant Laboratory, Inc., Anaheim, CA and San Jose, CA: www.soilandplantlaboratory.com
Soil Nutrient Analysis Laboratory, University of Connecticut, Storrs, CT: http://soiltest.uconn.edu/
Soil Testing and Plant Diagnostic Services, University of Missouri, Columbia, MO: http://soilplantlab.missouri.edu/
Stratford Agri Analysis Inc., Stratford, ON: www.stratfordagri.com
Ward Laboratories, Inc., Kearney, NE: www.wardlab.com
Waypoint Analytical, Anaheim, CA: www.waypointanalytical.com
Weld Laboratories, Inc., Greeley, CO: www.weldlabs.com
Western Laboratories, Parma, ID: www.westernlaboratories.com

These are a few of the many laboratories that offer soil, water, nutrient and plant tissue analyses. There are number of websites that also offer directories to laboratories such as the following:

Canadian Gardening-How to-Gardening Resources-Testing Your Soil: www.canadiangardening.com
Ministry of Agriculture and Lands, Nutrient Testing Laboratories: www.agf.gov.bc.ca/resmgmt/NutrientMgmt

Ontario Ministry of Agriculture, Food and Rural Affairs-Nutrient Testing-Accredited Soil Testing Laboratories in Ontario: www.omafra.gov.on.ca/english/crops/resource/soillabs.htm
Purdue University-University Related Plant Disease and Soil Testing Services, March 2010: www.apsnet.org/members/Documents/SoilLabsandPlantClinics.pdf
ATTRA-National Sustainable Agriculture Information Service-Alternative Soil Testing Laboratories: www.attra.org/attra-pub/soil-lab.html

BIOLOGICAL-CONTROL AGENTS

Note: This is not a complete list of companies selling and/or producing biological-control agents.

Producers

Applied Bio-Nomics Ltd., Sidney, BC: www.appliedbio-nomics.com
Associates Insectary, Santa Paula, CA: www.associatesinsectary.com
Becker Underwood, Ames, IA: www.beckerunderwood.com
Beneficial Insectary, Inc., Redding, CA: www.insectary.com
Biobest Canada Limited, Leamington, ON: www.biobest.ca
EnviroScience, Inc., Stow, OH: www.enviroscienceinc.com
Hydro Gardens-HGI Worldwide, Colorado Springs, CO: www.hydro-gardens.com
IPM Laboratories, Locke, NY: www.ipmlabs.com
Koppert Biological Systems, Inc., Howell, MI: www.koppert.com
Natural Insect Control, Stevensville, ON: www.naturalinsectcontrol.com
Pramukh Agriclinic, Madhi, Gujarat, India: Email: pramukhagriclinic@yahoo.co.in
Rincon-Vitova Insectaries, Inc., Ventura, CA: www.rinconvitova.com
Sesil Corporation, Chungcheongnam Do, South Korea: www.sesilipm.co.kr
Syngenta Bioline, Inc., Oxnard, CA: www.SyngentaBioline.com

Distributors

Bio Control S.A., Cartago, Costa Rica: Email: biocontrolsa@ice.co.cr
Distribuciones Imex S.A. de C.V., Jalisco, Mexico: www.distribucionesimex.com
EcoSolutions, Inc., Palm Harbor, FL: www.ecosolutionsbeneficials.com
Evergreen Growers Supply, Oregon City, OR: www.evergreengrowers.com
Global Horticultural, Inc., Beamsville, ON: www.globalhort.com
International Technical Services, Wayzatta, MN: www.greenhouseinfo.com or: www.intertechserv.com
MGS Horticultural, Inc., Leamington, ON: www.mgshort.com
Plant Products Co. Ltd., Brampton, ON: www.plantprod.com
Richters, Goodwood, ON: www.Richters.com
Sound Horticulture, Bellingham, WA: www.soundhorticulture.com

Sources of Information on Biological Control

Association of Natural Biocontrol Producers: www.anbp.org/biocontrollinks.htm
California Department of Pesticide Regulation: Suppliers of Beneficial Organisms in North America: www.cdpr.ca.gov/docs/pestmgt/ipminov/bensuppl.htm
Cornell University, College of Agriculture and Life Sciences, Ithaca, NY: www.biocontrol.entomology.cornell.edu/

North Carolina State University, Biological Control Information Center, Raleigh, NC: www.cipm.ncsu.edu/ent/biocontrol/links.htm
Oregon State University, Integrated Plant Protection Center, Corvallis, OR: www.ipmnet.org/
University of Arizona, Controlled Environment Agriculture Center (CEAC), Tucson, AZ: http://ag.arizona.edu/ceac/
University of California, Davis, CA: www.ipm.ucdavis.edu/
University of Hawaii Extension, Manoa, Hawaii: www.extento.hawaii.edu/kbase/
University of Minnesota, Minneapolis-St. Paul, MN: www.entomology.umn.edu/cues/dx/pests.htm
United States Department of Agriculture (USDA): www.usda.gov/wps/portal/usda/usdahome?navid=PLANT_HEALTH

REFERENCE

Leppla, N.C. and K.L. Johnson II. 2010. Guidelines for purchasing and using commercial natural enemies and biopesticides in Florida and other states. University of Florida IFAS Extension document IPM-146, Gainsville, FL. www.anbp.org/documents/Leppla_Paper_2010.pdf (accessed May 23, 2011).

SPECIAL HYDROPONIC EQUIPMENT

NFT Troughs

American Hydroponics, Arcata, CA: www.amhydro.com
CropKing, Lodi, OH: www.cropking.com
Dynacs, Sao Paulo, Brazil: www.dynacs.com.br
Green Automation Americas, Wellington, FL: www.greenautomation.com
Hidrogood Unipessoal Lda., Leiria, Portugal: http://hidrogood.com.pt
Hortiplan N.V., Belgium: www.hortiplan.com/MGS
Hydrocultura, Tlalpan, Mexico: www.hydrocultura.com.mx
HydroGarden Wholesale Supplies, Coventry, United Kingdom: www.hydrogarden.co.uk
Zwart Systems, Beamsville, ON: www.zwartsystems.ca

UV Sterilizers

Advanced UV, Inc., Cerritos, CA: www.advanceduv.com
Atlantic Ultraviolet Corp., Hauppauge, NY: www.ultraviolet.com
Aquafine Corporation, Valencia, CA: www.aquafineuv.com
Hortimax, B.V., The Netherlands: www.hortimax.com
Priva America Latina S.A. de C.V., Queretaro, Mexico: www.priva.mx
Priva B.V., The Netherlands: www.priva.nl
Priva International Beijing Ltd., Beijing, China: www.priva-asia.com
Priva North America, Inc., Vineland Station, ON: www.priva.ca
Priva UK, Watford, United Kingdom: www.priva.co.uk
Zwart Systems, Beamsville, ON: www.zwartsystems.ca

Water Chillers

Frigid Units, Inc., Toledo, OH: www.frigidunits.com

Vertical Plant Towers

Hydro-Stacker, Inc., Bradenton, FL: www.hydrostacker.com
Verti-Gro, Inc., Summerfield, FL: http://vertigro.com

Appendix 3
Units of Measurement: Conversion Factors

Units of	To Convert →	Into →	Multiply by
Length:			
25.401	Millimeters	Inches	0.0394
2.5401	Centimeters	Inches	0.3937
0.3048	Meters	Feet	3.2808
0.9144	Meters	Yards	1.0936
1.6093	Kilometers	Miles (statute)	0.6214
Area:			
645.160	Sq. Millimeters	Sq. Inches	0.001550
6.4516	Sq. Centimeters	Sq. Inches	0.1550
0.0929	Sq. Meters	Sq. Feet	10.7639
0.8361	Sq. Meters	Sq. Yards	1.1960
0.004046	Sq. Kilometers	Acres	247.105
2.5900	Sq. Kilometers	Sq. Miles	0.3861
0.4046	Hectares	Acres	2.4710
Volume:			
16.3872	Cu. Centimeters	Cu. Inches	0.0610
0.0283	Cu. Meters	Cu. Feet	35.3145
0.7646	Cu. Meters	Cu. Yards	1.3079
0.003785	Cu. Meters	Gallons (U.S.)	264.178
0.004545	Cu. Meters	Gallons (U.K.)	219.976
0.01639	Liters	Cu. Inches	61.0238
28.3205	Liters	Cu. Feet	0.03531
3.7850	Liters	Gallons (U.S.)	0.2642
4.5454	Liters	Gallons (U.K.)	0.2200
Weight:			
28.3495	Grams	Ounces (Av.)	0.0353
31.1035	Grams	Ounces (Troy)	0.0321
0.4536	Kilograms	Pounds (Av.)	2.2046
0.0004535	Metric Tons	Pounds (Av.)	2204.62
0.907185	Metric Tons	Tons (U.S.)	1.1023
1.016047	Metric Tons	Tons (U.K.)	0.9842
Light:			
5.000	Foot-candles	PAR (umol/m^2.s)	0.2 (sunlight)
7.6923	Foot-candles	PAR (umol/m^2.s)	0.13 (HPS)
6.6667	Foot-candles	PAR (umol/m^2.s)	0.15 (MH)
7.6923	Foot-candles	PAR (umol/m^2.s)	0.13 (LED)
11.574	PAR (umol/m^2.s)	DLI (mol/m^2.d)	0.0864 (24-h)*
0.0929	Foot-candles	lumen/m^2 (lux)	10.76
1.0	Lux	lumen/m^2	1.0

Units of	To Convert →	Into →	Multiply by
Power:			
1.0	Watt (w)	joule/s (j/s)	1.0
2.8×10^{-4}	Watt-hour (w.h)	joule/s (j/s)	3,600
2.8×10^{-10}	Kilo Watt-hour (kw.h)	joule/s (j/s)	3.6×10^{6}
Multiply by	**←Into**	**←To Convert**	

*If lights are on less than 24-h, this DLI must be adjusted by the fraction of time over 24 h. For example, 300 umol/m^2.s of PAR over a 24-h period of time will give 300 x 0.0864 = 25.92 mol/m^2.d of DLI. If the lights are to be operated only for 16 h the DLI is 16/24 x 25.92 = 17.28 mol/m^2.d. To compensate for the less than 24-h period of lighting, the PAR must be increased to get the DLI needed. Then adjust the PAR to: 300 x 25.92/17.28 = 450 umol/m^2.s, which will give: 450 umol/m^2.s x 0.0864 = 38.88 (over 24 h). That is 38.88 x 16/24 = 25.92 mol/m^2.d of DLI for 16 h.

Electrical Conductivity (EC):

1 decisiemen/m (dS/m) = 1 millisiemen/cm (mS/cm) + 100 mmhos/m =
1,000 uS/cm = 1 mmho/cm

Appendix 4
Physical Constants of Inorganic Compounds

Name	Formula	Density or Sp. Gravity	Solubility (gm/100 ml) Cold Water	Hot Water
Ammonium Nitrate	NH_4NO_3	1.725	118.3	871
Ammonium dihydrogen phosphate	$NH_4H_2PO_4$	1.803	22.7	173.2
Ammonium molybdate	$(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$	43		
Ammonium monohydrogen phosphate	$(NH_4)_2HPO_4$	1.619	57.5	106.0
Ammonium sulfate	$(NH_4)_2SO_4$	1.769	70.6	103.8
Boric Acid	H_3BO_3	1.435	6.35	27.6
Calcium carbonate	$CaCO_3$	2.710	0.0014	0.0018
Calcium chloride	$CaCl_2$	2.15	74.5	159
Calcium chloride hexahydrate	$CaCl_2{\cdot}6H_2O$	1.71	279	536
Calcium hydroxide	$Ca(OH)_2$	2.24	0.185	0.077
Calcium nitrate	$Ca(NO_3)_2$	2.504	121.2	376
Calcium nitrate tetrahydrate	$Ca(NO_3)_2{\cdot}4H_2O$	1.82	266	660
Calcium oxide	CaO	3.25-3.38	0.131	0.07
Calcium monophosphate	$Ca(H_2PO_4)_2{\cdot}H_2O$	2.220	1.8	decomposes
Calcium sulfate	$CaSO_4$	2.960	0.209	0.1619
Calcium sulfate dihydrate	$CaSO_4{\cdot}2H_2O$	2.32	0.241	0.222
Copper sulfate pentahydrate	$CuSO_4{\cdot}5H_2O$	2.284	31.6	203.3
Iron (II) hydroxide	$Fe(OH)_2$	3.4	0.00015	-
Iron (II) nitrate	$Fe(NO_3)_2{\cdot}6H_2O$	1.6	83.5	166.7
Iron (II) sulfate heptahydrate	$FeSO_4{\cdot}7H_2O$	1.898	15.65	48.6
Magnesium oxide	MgO_2	3.58	0.00062	0.0086
Magnesium orthophosphate	$Mg_3(PO_4)_2$	-	insoluble	insoluble
Magnesium monohydrogen phosphate heptahydrate	$MgHPO_4{\cdot}7H_2O$	1.728	0.3	0.2
Magnesium orthophosphate tetrahydrate	$Mg_3(PO_4)_2{\cdot}4H_2O$	1.64	0.0205	-
Magnesium sulfate heptahydrate	$MgSO_4{\cdot}7H_2O$	1.68	71	91
Manganese dichloride tetrahydrate	$MnCl_2{\cdot}4H_2O$	2.01	151	656
Manganous (II) hydroxide	$Mn(OH)_2$	3.258	0.0002	-
Manganous nitrate	$Mn(NO_3)_2{\cdot}4H_2O$	1.82	426.4	infinite
Manganous dihydrogen phosphate	$Mn(H_2PO_4)_2{\cdot}2H_2O$	-	soluble	-
Manganous monohydrogen phosphate	$MnHPO_4{\cdot}3H_2O$	-	slightly soluble	decomposes
Manganous sulfate	$MnSO_4$	3.25	52	70
Manganous sulfate tetahydrate	$MnSO_4{\cdot}4H_2O$	2.107	105.3	111.2
Nitric acid	HNO_3	1.5027	infinite	infinite
Phosphoric acid (ortho)	H_3PO_4	1.834	548	very soluble

Name	Formula	Density or Sp. Gravity	Solubility (gm/100 ml) Cold Water	Hot Water
Phosphoric anhydride	P_2O_5	2.39	decomposes to H_3PO_4	
Potassium carbonate	K_2CO_3	2.428	112	0.156
Potassium carbonate dihydrate	$K_2CO_3 \cdot 2H_2O$	2.043	146.9	331
Potassium hydrogen carbonate	$KHCO_3$	2.17	22.4	60
Potassium carbonate trihydrate	$2K_2CO_3 \cdot 3H_2O$	2.043	129.4	268.3
Potassium chloride	KCl	1.984	34.7	56.7
Potassium hydroxide	KOH	2.044	107	178
Potassium nitrate	KNO_3	2.109	13.3	47
Potassium orthophosphate	K_3PO_4	2.564	90	soluble
Potassium dihydrogen phosphate	KH_2PO_4	2.338	33	83.5
Potassium monohydrogen phosphate	K_2HPO_4	-	167	very soluble
Potassium sulfate	K_2SO_4	2.662	12	24.1
Zinc carbonate	$ZnCO_3$	4.398	0.001	-
Zinc chloride	$ZnCl_2$	2.91	432	615
Zinc orthophosphate	$Zn_3(PO_4)_2$	3.998	insoluble	insoluble
Zinc dihydrogen phosphate	$Zn(H_2PO_4)_2 \cdot 2H_2O$	-	decomposes	-
Zinc orthophosphate tetrahydrate	$Zn_3(PO_4)_2 \cdot 4H_2O$	3.04	insoluble	insoluble
Zinc sulfate heptahydrate	$ZnSO_4 \cdot 7H_2O$	1.957	96.5	663.6

Appendix 5
Greenhouse and Hydroponic Suppliers

BIOCONTROL AGENTS

Microbials/Bioagents

ACM-Texas, LLC, Fort Collins, CO: www.ampowdergard.com
AgriDyne Technologies, Inc., (BioSys, Inc.), Rosenberg, TX: www.biosysinc.com
Bayer Corporation, Kansas City, MO: http://usagri.bayer.com
BioBest Canada Ltd., Leamington, ON: www.biobest.ca
BioSafe Systems LLC., East Hartford, CT: www.biosafesystems.com
BioWorks, Inc., Victor, NY: www.bioworksinc.com
Dow AgroSciences LLC: www.dowagro.com
EcoSmart Technologies, Inc., Franklin, TN: www.ecosmart.com
Growth Products, Ltd., White Plains, NY: www.growthproducts.com
International Technology Services, Wayzatta, MN: www.intertechserv.com
McLaughlin Gormley King Company (MGK), Minneapolis, MN: www.pyganic.com
Monterey AgResources, Fresno, CA: www.montereyagresources.com
Mycogen Corporation, San Diego, CA: www.dowagro.com
Natural Industries, Inc., Houston, TX: www.naturalindustries.com
Olympic Horticultural Products Co., (OHP), Mainland, PA: www.ohp.com
Phyton Corporation: www.phytoncorp.com
The Organic Materials Review Institute (OMRI), Eugene, OR: www.omri.org
Valent BioSciences Corporation, Libertyville, IL: www.valentpro.com

Pollinators (Bombus sp.)

Bees West, Inc., Freedom, CA: www.beeswestinc.com
Biobest Belgium N.V., Westerlo, Belgium: www.biobest.be
Biobest Canada Ltd., Leamington, ON: www.biobest.ca
Distribuciones Imex S.A. de C.V., Jalisco, Mexico: www.distribucionesimex.com
International Technical Services, Wayzatta, MN: www.intertechserv.com
Koppert B.V., Berkel en Rodenrijs, The Netherlands: www.koppert.nl
Koppert Canada Limited, Scarborough, ON: www.koppert.com
Koppert Mexico, S.A. de C.V., El Marques, Queretaro, Mexico: www.koppert.com.mx
Koppert Biological Systems, Inc.-USA, Howell, MI: www.koppert.com

GREENHOUSE STRUCTURES, COVERINGS, AND EQUIPMENT

Acme Engineering & Mfg. Corp., Muskogee, OK: www.acmefan.com
Advancing Alternatives, Schuylkill Haven, PA: www.advancingalternatives.com

AgraTech, Inc., Pittsburg, CA: www.agratech.com
American Coolair Corp., Jacksonville, FL: www.coolair.com
AmeriLux International, LLC, DePere, WI: www.ameriluxinternational.com
Argus Control Systems Ltd., White Rock, BC: www.arguscontrols.com
AT Films, Inc., Edmonton, AB: www.atfilmsinc.com
Atlas Manufacturing, Inc., Alapaha, GA: www.atlasgreenhouse.com
Berco, Inc., St. Louis, MO: www.bercoinc.com
BFG Supply Co., Burton, OH: www.bfgsupply.com
Biotherm Hydronic, Inc. (TrueLeaf Technologies), Petaluma, CA: www.trueleaf.net
B & K Installation Co. Inc., Homestead, FL: www.bk-installations.com
Bom Greenhouses, Naaldwijk, The Netherlands: www.bomgreenhouses.com
Canadian Hydrogardens Ltd., Ancaster, ON: www.hydrogardens.ca
Climate Control Systems, Inc., Leamington, ON: www.climatecontrol.com
Conley's Greenhouse Manufacturing & Sales, Montclair, CA: www.conleys.com
Cravo Equipment Ltd., Brantford, ON: www.cravo.com
CropKing, Inc., Lodi, OH: www.cropking.com
Dalsem Horticultual Projects B.V., Den Hoorn, The Netherlands: www.dalsem.nl
DeCloet Greenhouse Manufacturing Ltd., Simcoe, ON: www.decloetgreenhouse.com
Delta T Solutions, San Marcos, CA: www.deltatsolutions.com
Evonik Cyro Canada, Inc., Toronto, ON: www.acrylitebuildingproducts.com
Fogco Systems, Inc., Chandler, AZ: www.fogco.com
Foremostco, Inc., Miami, FL: www.foremostco.com
FormFlex Horticultural Systems, Beamsville, ON: www.formflex.ca
Foundation DACE, Nijkerk, The Netherlands: www.dace.nl
Grayhawk Greenhouse Supply, Swanton, OH: www.grayhawkgreenhousesupply.com
Green-Tek, Edgerton, WI: www.green-tek.com
Growers Greenhouse Supplies, Inc., Vineland Station, ON: www.ggs-greenhouse.com
Growers Supply, Dyersville, IA: www.growerssupply.com
Grupo Inverca S.A., Almazora, Spain: www.invercagroup.com
Harnois Greenhouses, St-Thomas-de-Joliette, QC, Canada: www.harnois.com
Herve Savoure, Reston, VA: www.richel-usa.com
Holland Greenhouses, Lansingerland, The Netherlands: www.holland-greenhouses.nl
Jaderloon Co. Inc., Columbia, SC: www.jaderloon.com
JVK Ltd., St. Catharines, ON: www.jvk.net
Kees Greeve B.V., Bergschenhoek, The Netherlands: www.keesgreeve.nl
KGP Greenhouses, Maasdijk, The Netherlands: www.kgpgreenhouses.com
Koolfog, Inc., Palm Desert, CA: www.koolfog.com
Kubo Greenhouse Projects, Monster, The Netherlands: www.kubo.nl
LL Klink & Sons, Inc., Columbia Station, OH: www.LLKlink.com
LS Svensson, Kinna, Sweden: www.ludrigsvensson.com
Ludy Greenhouse Manufacturing Corporation, New Madison, OH: www.ludy.com
Lumite, Inc., Gainesville, GA: www.lumiteinc.com
Lux Lighting Co., Ltd., GuangMing New District, Shenzhen, China: www.growlight.cn
McConkey Co. Inc., Sumner, WA: www.mcconkeyco.com
Mee Industries, Inc., Monrovia, CA: www.meefog.com
Metazet Zwethovve B.V., Wateringen, The Netherlands: www.metazet.com
Nexus Corporation, Northglenn, CO: www.nexuscorp.com
Oregon Valley Greenhouses, Inc., Aurora, OR: www.ovg.com
PARsource Lighting Solutions, Petaluma, CA: www.parsource.com.
Paul Boers Ltd., Vineland Station, ON: www.paulboers.com

Plastika Kritis S.A., Crete, Greece: www.plastikakritis.com
P.L. Light Systems, Inc., Beamsville, ON: www.pllight.com
Polygal, Inc., Charlotte, NC: www.polygal.com
Poly-Tex, Inc., Castle Rock, Mn: www.poly-tex.com
Powerplants Australia Pty Ltd., Victoria, Australia: www.powerplants.com.au
Prins Greenhouses, Abbotsford, BC: www.prinsgreenhouses.com
Quasar Light Co., Ltd., Shenzhen Guangdong, China: www.quasarled.com
Richel Group, Eygalieries, France: www.richel.fr
Rough Brothers, Inc., Cincinnati, OH: www.roughbros.com
Smart Fog, Inc., www.smartfog.com
South Essex Fabricating Inc., Leamington, ON: www.southsx.com
Southwest Agri-Plastics, Inc., Dallas, TX: www.swapinc.com
Structures Unlimited, Sarasota, FL: www.structuresunlimited.net
Stuppy Greenhouse Mfg. Inc., Kansas City, MO: www.stuppy.com
Sunlight Supply, Inc., Vancouver, WA: www.sunlightsupply.com
TrueFog, USA, Desert Hot Springs, CA: www.truefog.com
Val-Co Environmental & Greenhouse Systems, Bird-In-Hand, PA: www.valcogreenhouse.com
Val-Co Greenhouse, Lopik, The Netherlands: www.valcogreenhouse.com
Van der Hoeven B.V., Gravenzande, The Netherlands: www.vanderhoeven.nl
Van Wingerden Greenhouse Company, Mills River, NC: www.van-wingerden.com
Venlo Greenhouse Systems, Inc., Spotsylvania, VA: www.venloinc.com
Verbakel/Bomdas B.V., De Lier, The Netherlands: www.verbakel-bomkas.com
V & V Group, De Lier, The Netherlands: www.venv-holland.nl
Wadsworth Control Systems, Arvada, CO: www.wadsworthcontrols.com
Westbrook Greenhouse Systems, Beamsville, ON: www.westbrooksystems.com
XS Smith, Inc., Washington, NC: www.xssmith.com
Zwart Systems, Beamsville, ON: www.zwartsystems.ca

GREENHOUSE SHADING MATERIALS

Mardenkro North America, Chilliwack, B.C.: www.mardenkro.com

GROWING MEDIA AND SUPPLIES

Berger Peat Moss, St. Modeste, QC, Canada: www.bergerweb.com
Conrad Fafard, Inc., Agawam, MA: www.fafard.com
CropKing, Inc., Lodi, OH: www.cropking.com
DeWitt Company Inc., Sikeston, MO: www.dewittcompany.com
Dutch Plantin B.V., Helmond, The Netherlands: www.dutchplantin.com
Euro Substrates (Pvt) Ltd., Pitakotte, Sri Lanka (Forteco Coco Coir): www.eurosubstrates.com
Fibrgro Horticultural Rock Wool, Sarnia, ON: www.fibrgro.com
Grodan, Roermond, The Netherlands: www.grodan.nl
Grodan Inc., Milton, ON: www.grodan.com
Hydro-Gardens, Inc., Colorado Springs, CO: www.hydro-gardens.com
Hydrofarm, Horticultural Products, Petaluma, CA: www.hydrofarm.com
Jiffy Products International BV, Hoek Van Holland, The Netherlands: www.jiffypot.com
Michigan Peat Co., Houston, TX: www.michiganpeat.com
Plant Products Co. Ltd., Brampton, ON: www.plantprod.com
Premier Tech Horticulture, Riviere-du-Loup, QC: www.premierhort.com
Saint-Gobain Cultilene B.V., Tilburg, The Netherlands: www.cultilene.nl

Smithers-Oasis North America, Kent, OH: www.smithersoasis.com
Sun Land Garden Products, Inc., Watsonville, CA: www.sunlandgarden.com
Sun Gro Horticulture, Vancouver, BC: www.sungro.com
The Scotts Miracle-Gro Company, Marysville, OH: www.thescottsmiraclegrocompany.com
Whittemore Company, Inc., Lawrence, MA: www.whittemoreco.com

IRRIGATION EQUIPMENT

American Horticultural Supply, Inc., Camarillo, CA: www.americanhort.com
Amiad Filtration Systems Ltd., Oxnard, CA: www.amiadusa.com
H.E. Anderson Company, Muskogee, OK: www.heanderson.com
BFG Supply Co., Burton, OH: www.bfgsupply.com
Climate Control Systems Inc., Leamington, ON: www.climatecontrol.com
CropKing, Inc., Lodi, OH: www.cropking.com
Dosatron International Inc., Clearwater, FL: www.dosatronusa.com
Dosmatic U.S.A./International, Inc., Carrollton, TX: www.dosmatic.com
Dramm Corporation, Manitowoc, WI: www.dramm.com
Growing Systems, Inc., Milwaukee, WI: www.growingsystemsinc.com
Hummert International, Earth City, MO: www.hummert.com
Hunter Industries, Inc., San Marcos, CA: www.hunterindustries.com
Hydro-Gardens, Inc., Colorado Springs, CO: www.hydro-gardens.com
Jain Irrigation Inc., Watertown, NY: www.jainirrigationinc.com
Keeler-Glasgow Company, Inc., Hartford, MI: www.keeleer-glasgow.com
Maxijet, Inc., Dundee, FL: www.maxijet.com
Netafim Irrigation, Inc., Fresno, CA: www.netafimusa.com
Plant Products Co. Ltd., Brampton, ON: www.plantprod.com
Rain Bird Agri-Products Co., Glendora, CA: www.rainbird.com
Roberts Irrigation Company, Inc., Plover, WI: www.robertsirrigation.net
Senninger Irrigation, Inc., Clermont, FL: www.senninger.com
Rain For Rent, Bakersfield, CA: www.rainforrent.com
The Toro Company, Riverside, CA: www.toro.com
Zwart Systems, Beamsville, ON: www.zwartsystems.ca

SEEDS

American Takii, Inc., Salinas, CA: www.takii.com
Asgrow Seed Co./Monsanto Company, Oxnard, CA: www.asgrowandekalb.com & www.monsantovegetableseeds.com
Ball Seed Co., West Chicago, IL: www.ballhort.com
Corona Seeds, Camarillo, CA: www.coronaseeds.com
De Ruiter Seeds, Inc., /Monsanto Company, Oxnard, CA: www.deruiterseeds.nl & www.monsantovegetableseeds.com
Enza Zaden, Salinas, CA: (www.enzazaden.com)
Ferry-Morse Seed Company, Fulton, KY: www.ferry-morse.com
Harris Moran Seed Company, Modesto, CA: www.harrismoran.com
Harris Seeds, Rochester, NY: www.harrisseeds.com
HPS (Horticultural Products & Services), Randolph, WI: www.hpsseed.com
Hazera Seeds, Inc., Coconut Creek, FL: www.hazerainc.com
A.H. Hummert Seed Co., St. Joseph, MO: www.hummertseed.com
Johnny's Selected Seeds, Winslow, ME: www.johnnyseeds.com

Monsanto Company, Oxnard, CA: www.monsantovegetableseeds.com
Nickerson-Zwaan, Made, The Netherlands: www.nickerson-zwaan.com
Northrup King Co., Minneapolis, MN: www.nk.com
Nunhems USA, Inc., Parma, ID: www.nunhemsusa.com
Ornamental Edibles, San Jose, CA: www.ornamentaledibles.com
PanAmerican Seed Co., West Chicago, IL: www.panamseed.com
Paramount Seeds Inc., Palm City, FL: www.paramountseeds.com
Park Seed Co., Greenwood, SC: www.parkseed.com
Penn State Seed Co., Dallas, PA: www.pennstateseed.com
Richters, Goodwood, ON: www.Richters.com
Rijk Zwaan USA, Inc., Salinas, CA: www.rijkzwaanusa.com
Rijk Zwaan De Lier, De Lier, The Netherlands: www.rijkzwaan.com
Royal Sluis, Inc., (Seminis Vegetable Seeds, Inc.), St. Louis, MO: www.seminis.com
Sakata Seed America, Inc., Morgan Hill, CA: www.sakata.com
Stokes Seeds, Inc., Buffalo, NY or Thorold, ON: www.stokeseeds.com
Syngenta Seeds, Inc., (Rogers Seeds), Boise, ID: www.syngenta-us.com
Thompson & Morgan, Lawrenceburg, IN: www.tmseeds.com
Vitalis Organic Seeds, Salinas, CA (division of Enza Zaden): www.usa.vitalisorganic.com
Yuksel Seeds, Mexico: www.yukselseeds.com

SPROUT SUPPLIES

Caudill Seed Company, Inc., Louisville, KY: www.caudillseed.com
International Specialty Supply, Cookeville, TN: www.sproutnet.com

Taylor & Francis
Taylor & Francis Group
http://taylorandfrancis.com

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General

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Note: This list of publications has not been updated for 2021 because there are so many new publications on all aspects of hydroponics and greenhouse horticulture that the time needed to add new publications is not warranted when searches by internet search engines such as Google can provide that information.

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